AN INVESTIGATION INTO DRY AND WET TEXTILE FRICTION AND LUBRICATION IN PRACTICAL APPLICATIONS

By

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Thesis submitted to De Montfort University in partial fulfilment of the requirements for the Degree of Doctor of Philosophy

Research conducted at Acordis UK Ltd (formerly Courtaulds)

February, 1999

For my mother Ann and for my late father Terry

ABSTRACT

The lubrication of dry viscose fibres by a two component finish, and the lubrication of wet lyocell fabric against metal, with various aqueous lubricant systems, has been studied.

Secondary ion mass spectrometry (SIMS) was investigated as a means of providing direct chemical information from finished fibre surfaces. The composition and distribution of a two component finish applied to viscose fibres was determined successfully.

When applying finish from a bath, the surface composition of the finished fibres was not controlled by the bath conditions. Increasing the concentration of finish in the bath did, however, increase the total amount of finish deposited, and increasing the concentration of antistat relative to lubricant in the bath increased the amount of antistat relative to lubricant deposited on the finished fibres.

Fibre friction was determined using the capstan method. The friction forces, measured for finished viscose fibres, were correlated with the finish application conditions. Increasing the emulsion concentration in the finish bath reduced fibre/metal friction, but finish component ratio, emulsion concentration, dip time and bath temperature did not affect fibre/fibre friction.

Spray applying the finish resulted in unfinished regions on the fibre surfaces and the electrical resistance of fibre bundles was not reduced. Bath application of finish did lower electrical resistance in comparison with unfinished fibre, but none of the bath deposition variables had a significant effect on electrical resistance.

Wet fabric/metal friction and fabric abrasion damage after rubbing were investigated. A wide variety of lubricant systems reduced low speed (static), wet fabric/metal friction. Covering the metal surface with poly(ethylene) film, however, gave the best reduction in static friction. Dynamic friction was reduced more by dye liquor and selected components of the liquor than by any of the lubricant systems.

Wet abrasion tests with selected lubricants showed the best overall reduction in abrasion damage was achieved when the metal rubbing surface was covered with poly(ethylene) film. No significant correlation was seen between measured friction parameters and the level of abrasion damage.

The lubricants examined did not, overall, increase wet fabric crease recovery angles.

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LIST OF ABBREVIATIONS

amu	Atomic mass unit
ANOVA	Analysis of variance
ASTM	American Society for Testing and Materials
ATR	Attenuated total reflection
CR	Crease recovery
CSD	Combined standard deviation
CV	Coefficient of variation
DEA	Diethanolamide
DMDHEU	Dimethylol dihydroxy ethylene urea
DSDMAC	Distearyl dimethyl ammonium chloride
EMA	Ethyl methacrylate
FTIR	Fourier transform infra-red spectroscopy
HEMA	Hydroxyethyl methacrylate
HLB	Hydrophile-lipophile balance
HPLC	High performance liquid chromatography
IPA	Iso propyl alcohol
IR	Infrared
LSD	Least significant difference
MCT	Mercury cadmium telluride
PAA	Poly(acrylic acid)
PAm	Poly(acrylamide)
PAN	Poly(acrylonitrile)

P2DL	Poly(ethylene glycol) 200 dilaurate
PDMS	Poly(dimethyl siloxane)
PE	Poly(ethylene)
PEG	Poly(ethylene glycol)
PEO	Poly(ethylene oxide)
PLS	Partial least squares
POE	Poly(oxyethylene)
PPO	Poly(propylene oxide)
PTFE	Poly(tetrafluoro ethylene)
SDS	Sodium dodecyl sulphate
SEM	Scanning electron microscope
SIMS	Secondary ion mass spectrometry
TRI	Textile Research Institute
UV	Ultraviolet
XPS	X-ray photoelectron spectroscopy

ACKNOWLEDGEMENTS

I have received much help and support during this project for which I am truly grateful. First of all, a big 'thank you' goes to my supervisor, Dr David Bishop, for all of his suggestions, patience and hours of reading and correcting drafts of chapters in this thesis. It was David who suggested four years ago that perhaps I should consider doing a PhD rather than MSc – I'm glad he persuaded me.

I would like to thank Acordis UK Ltd (formerly Courtaulds) for funding this project. In particular Hilda Coulsey and Eamonn Gallagher are thanked for signing on the dotted line and for allowing me the time juggle a full time job and a part time PhD project.

Dr Suky Singh is thanked for teaching me about surface science. Along with Dr Mike Keane, we had some good times as the 'Surface Fat Boys' in GE13, and especially in the canteen.

Thank you to Drs Simon Nunn and Ian Blackham for running the IR and XPS instruments. Without their help obtaining spectra would have been a lot more difficult. Thanks are also due to Neil Gallagher who rescued a big section of viscose tow from Grimsby – ideal for friction and surface science experiments.

Thanks to Dennis Waldron in microscopy for showing me how to use the scanning electron microscope, and to Anne Whineray, Angie Gallagher, Ann Dale, Denise Rider and all the girls in Testing Services who showed me how to use an Instron and other textile testing equipment.

Thanks are due to Sarah Hawkins, Richard Wilson and Rosemary Dovey, who all helped in the literature searches. Their knowledge of databases proved very useful.

Neil Morley and Wendy Neale in graphics are thanked for their help in electronically capturing images which would otherwise exist on paper only.

Diane Smith and Tracey O'Leary are thanked for showing me how to do a soxhlet extraction properly.

Having written this list of acknowledgements, it is now obvious to me, how important other people are in getting things done. Thank you everyone!

Last, but certainly not least, thank you Suzanne for a lot of patience, understanding and support through the highs and lows during this work. It would have been a lot harder to go through this alone, I was very fortunate as I didn't have to.

AUTHOR'S DECLARATION

The work described in this thesis was carried out at Acordis UK, Ltd (formerly Courtaulds), Coventry. It has not been submitted for any other degree and is the original work of the author except where acknowledged by reference.

Work in this thesis was the basis of the following paper:

W.B. LINETON, N.S. NUNN, D.P. BISHOP, An Application of Secondary Ion Mass Spectrometry to the Analysis of Fibre Finishes. *J. Text. Inst.*, accepted for publication 4th September 1998.

CHAPTER 1

AN INTRODUCTION TO TEXTILE FRICTION AND LUBRICATION AND OBJECTIVES OF THE STUDY

Lubricants are essential in many stages of textile production. The present work is concerned with two particular types of textile lubrication:

(i) fibre finishing to modify friction in carding, drafting and spinning processes and

(ii) lubrication to reduce fabric damage during dyeing and finishing.

Although both of these aspects of lubrication are relevant to many different fibre and fabric types, the present study is confined to regenerated cellulose fibres and fabrics.

(i) Fibre Finishes

Fibre finishes are essential processing aids when converting staple fibre to yarn through carding, drafting and spinning (Billica, 1984a). These finishes must lubricate, control static electricity generation and provide cohesion during processing (Crossfield, 1984). Consequently they usually contain several components. In the later stages of textile manufacture, typically after knitting or weaving but before dyeing, fibre finishes are removed by scouring.

It is desirable to know how the concentrations of the components in the fibre finishing bath, the bath temperature, and immersion time affect the final composition, distribution and

performance of the finish deposited on the fibre. These are all real variables in a fibre production plant. More reliable information on the relative importance of these variables will contribute to the optimization of cost and performance of fibre finishes. An objective of the present work was therefore to obtain this type of information for a model finish containing lubricant and antistat components. Whereas an antistat is essential to an effective fibre finish, antistatic control and measurement is a considerable subject in its own right and did not form part of this project. The performance of fibre finishes has therefore been measured in terms of their lubricating properties with only a brief examination of changes in electrical behaviour.

Relationships between finish deposition variables (time, temperature, concentration and component ratio) and the surface composition of the finished fibres, as well as the resulting lubrication performance are of interest. At present there is no generally available method for measuring directly the chemical composition and distribution of finish on fibres. A further objective was to show that with some methodology development, Secondary Ion Mass Spectrometry (SIMS) could be used to obtain such information. An appropriate friction measurement technique was available for quantifying lubrication performance. From these two types of measurement it should be possible to establish links between deposition conditions, the resulting surface and bulk compositions of finish on fibres, and their lubrication performance and this was another aim of the study.

(ii) Wet Fabric Lubrication

Abrasion damage often occurs during dyeing and finishing of fabrics, particularly when folds in fabrics are dragged against metal machine surfaces. There are many commercially available wet lubricants which reduce this problem, and although there are a number of

patents which describe specific lubricant compositions, there is little evidence in the literature of scientific study or understanding of the mechanisms of wet textile lubrication. The first objective of this part of the project was therefore to evaluate the wet friction-reducing and abrasion-damage-prevention properties of a range of chemicals used as typical wet lubricants (e.g. wax dispersions, surfactants and polyacrylics). It was also proposed to study bio-polymers as novel lubricants.

The aim of this part of the project was to relate wet friction to abrasion damage for fabric against metal (stainless steel) for a range of wet lubricants with a view to improving understanding of the lubricant structure and property requirements for effective performance.

1.1 DRY LUBRICATION OF FIBRES

1.1.1 Functions of a Finish

A finish should provide lubrication to fibres as they slide over each other and over machinery guides. Lubrication is necessary to prevent damage and wear due to friction (Crossfield, 1984). Static protection is also required. When two dissimilar surfaces slide over each other electrons are transferred leading to a build up of charge. This causes fibres to stick to each other or to machine surfaces via electrostatic attraction, or to fly apart via repulsion (Billica, 1984a). Water is good at dissipating charge and some antistats rely on its presence (Billica, 1984a). Cohesion is needed to hold fibres to together when they are processed into a construction such as a card web or sliver (Crossfield, 1984), without it the fibre assembly would fall apart.

If the finish lowers the friction between fibres by too much, failure can occur when a yarn is stressed, and the fibres slide over each other until the yarn comes apart. This was

demonstrated by Broughton *et al.* (1992), when a silicone polymer on a polyester yarn caused it to fail under load, due to low inter-fibre friction. Silicones, well known in fabric softening treatments (Sandner, 1995) and quaternary ammonium salts used in fabric conditioners, and also known for their inter-fibre lubricating effect (Davidsohn and Milwidsky, 1972, Clint, 1990), are distinguished from the type of lubricants used in fibre finish formulations.

Most finishes are applied as emulsions in water (Redston *et al.*, 1973). Formulations contain primary components (Kleber, 1977, Billica, 1984b) which are:

- lubricant
- antistat
- emulsifier,

and some secondary components (Billica, 1984b) which are selected from:

- anti-corrosive agents and antioxidants
- pH modifiers
- bactericides and fungicides
- cohesive agents
- viscosity modifiers
- dyeing and levelling agents
- adhesion promoters
- perfumes.

1.1.2 Finish Chemistry

The primary components of fibre finishes often tend to be chemically similar and some components may act in more than one role. For example, quaternary ammonium salts are lubricants which also have antistatic properties, and polyethylene glycol (PEG) esters are lubricants which also act as emulsifiers. The general chemical types of the primary components are shown below.

Lubricants:

A number of finish lubricants are based on paraffinic oils, also known as "white oils" (Kleber, 1977). Fatty acid esters of natural oils (coconut, corn, peanut, palm, rice, sperm) are also used (Postman, 1980). Nevrekar and Palan (1992) suggest polyethers and silicones as lubricants, whilst Billica (1984b) proposes ethoxylated alcohols and synthetic waxes. Sinha (1977) describes fatty acid compounds, with between 6 and 18 carbon atoms in the alkyl chains, as having excellent lubricity. Linear molecules give good lubrication. Branched molecules are not as effective and may need added cohesion, however, they tend to be more temperature stable (Redston *et al.*, 1973). A simple lubricating emulsion for wool was described by Townend (1940). This contained 50% oleine and 50% water. Finishes can be much more complex though, and as an example Postman (1980) lists eleven components in a typical formulation.

Emulsifiers:

Anionic, cationic, nonionic or amphoteric surfactants are usually employed. Emulsifying performance depends on the hydrophile-lipophile balance (HLB) number (Myers, 1988), which is a measure of the water loving or oil loving character of the molecule. Redston *et al.*

(1973) suggest that the HLB number of an emulsifier should be above 4. Obetz (1978) describes spin finish formulations for polyester which contain 30% to 40% emulsifier.

Billica (1984b) lists alkane sulphonates, alkyl-sulphosuccinate salts, fatty amines and their ethoxylates, quaternary amines and their ethoxylates, polyglycols (including esters and ethers) and alkyl phenols as suitable emulsifiers.

Nevrekar and Palan (1992) propose fatty acid soaps, sulphated vegetable oils, amino acids and their salts and betaines as emulsifiers.

Postman (1980) suggests that ethoxylated fatty acids and alcohols should have alkyl chains containing between 12 and 22 carbon atoms. The compounds can be partial or complete esters and preferably contain 20 to 50 ethylene oxide units in the molecules.

Antistats:

Kleber (1977) states that derivatives of phosphorous pentoxide (P_4O_{10}) are used as antistatic agents. Also used are amine oxides with alkyl chains containing between 5 and 22 carbon atoms.

In a paper by Postman (1980) cationic fatty alkyl compounds of nitrogen or phosphorous, in the form of tertiary or quaternary salts, are described as suitable antistats. These are preferred because of their substantivity and orientability on fibre surfaces. The alkyl section of the molecule usually contains between 8 and 20 carbon atoms. Phosphate esters with between 6 and 10 carbon atoms in the alkyl portion are also popular. Potassium alkyl phosphates can be either mono or di-esters.

Nonionic poly(oxyethylene) derivatives of fatty acids, alcohols, amines and amides, and anionic soaps and esters of sulphuric acid are proposed by Sinha (1977) in addition to the cationic quaternary compounds already mentioned. Sinha also states that water is an important factor when choosing an antistat. Water is a comparatively good conductor of electricity and it can prevent charge build up in fibre processing, so hygroscopic materials are potentially good antistatic agents on non-conducting fibres.

1.1.3 The Criteria for a Good Finish

Some of the properties of a good finish (Redston *et al.* 1973, Kleber 1977, Postman 1980, Crossfield 1984) are:

- chemically stable
- physically stable (emulsions)
- emulsifiable
- controllable
- non-reactive
- non-corrosive
- non-toxic
- medically acceptable for its intended use
- good at wetting out fibre surfaces
- heat resistant up to temperatures of the order of 200°C
- easy to remove in subsequent washing/scouring
- non-volatile
- non-colouring or staining
- resistant to malodour development.

1.1.4 Methods of Applying Finish

The desired balance of properties required from textile finishes is achieved by using formulations having several components. Multi-component emulsions are applied at concentrations typically around 1 to 5% in water. In some cases dilute oils or 100% oils are applied to fibres.

There are a number of methods of applying finish to fibres. Bath application (Bergman and Kurtz, 1986) is suitable for tow, where continuous bundles of filaments can be fed into and submerged in a vessel containing the finish. Surface active components are adsorbed to the fibres before they exit the bath after which they pass on to dryers.

Lick rollers, also called kiss rolls (Bergman and Kurtz, 1986), are suitable for application to tow. The tow band passes over a rotating roller which is semi-submerged in a reservoir of finish. Emulsion is carried around and transferred to the fibres as the roller rotates. There can be fluctuations in the amount of finish applied if this method is used incorrectly.

Metered pumps (King, 1977) can dispense finish to narrow tows or single filaments. Finish is dispensed at a constant rate onto moving fibre. It is a suitable method for applying neat oils.

When finish is applied to a bed of staple fibres, the methods commonly used are (i) overspray where the emulsion is sprayed onto the fibre bed prior to drying, (ii) serrated tray, where the drops of finish overflow from a tank suspended above the fibre bed, and (iii) bubbler - this is a horizontal pipe with a number of holes along its length through which finish is forced and bubbled out onto the bed (Pike, 1992, Szokalo, 1994).

1.1.5 Analysis of Finishes

Finishes are needed to control the friction and cohesion of textile fibres during processing. The type and amount of finish delivered to the fibres affects friction and processing properties. The distribution of finish is also important, since an unevenly distributed finish might be expected to give inconsistent processing such as uneven card slivers and yarns.

Methods exist to measure the amount of finish deposited onto fibres and yarns. Some techniques have also been developed to monitor the distribution of finish on fibre/yarn surfaces. The American Society for Testing and Materials (ASTM) has defined a "Standard Test Method for Extractable Matter in Textiles" [ASTM D2257]. It relies on soxhlet extraction of fibres, yarns or fabrics using halogenated hydrocarbon and alcohol solvents. Solvent is removed from the extract and the % finish on fibre is determined gravimetrically. Alternatively the solvent, containing the extract, can be analysed by infra-red, refractive index measurement or by specific gravity (Hohing, 1977). A problem with this approach is making sure the extract contains only finish and that all of the finish is removed. Other materials such as fibre dope or spin bath additives may affect the result if they are soluble in the solvent.

Taylor, Anderson and Brydon (1994) used high performance liquid chromatography (HPLC) to produce fingerprint chromatograms of finishes. Finished polyester fibres were extracted in petroleum ether. The residue was dissolved in methanol and dichloromethane following evaporation of the ether. Both fractions were examined by HPLC and it was shown that composition changes due to heating the fibres could be followed.

There are other ways of extracting finish. Jordan, Taylor and Seemuth (1995) used carbon dioxide in a supercritical fluid extraction. A seven component finish was extracted from polyester and analysed by Fourier transform infra-red spectroscopy (FTIR). The extractability of the components ranged from 25-100%. Hence a calibration is required if extracts of unknown component ratios are to be analysed. In later work by Liescheski *et al.* (1996) supercritical fluid extraction was used to measure the % of poly(dimethyl siloxane) finishing oil on polyurethane fibres.

Attempts have also been made to observe finishes directly on the surface of fibres and yarns, without the need for extraction. In these methods the distribution of the finish is observed by adding tracers to the finish prior to deposition. The location of the finish on fibre or yarn can be observed by a suitable detection system. Work at the TRI, Princeton demonstrated that finish coverage on yarns can be deduced by microfluorometry using an ultraviolet (UV) fluorescent tracer. Results were complemented by wettability scans along the yarns (TRI Annual Report, 1992).

Crossfield and Cohen (1977) used an X-ray probe to monitor the amount of finish on fibres. They found a linear relationship between X-ray count, using a tracer, and finish level, determined by gravimetric extractions. Finish levels could therefore be determined without extraction.

Agafanova *et al.* (1978) observed the coefficient of friction along yarns and attempted to relate this to the uniformity of the surface. They demonstrated clear differences between various finish formulations.

More recently, Leijala and Hautojärvi (1998) have used scanning force microscopy to image spin finish layers on polypropylene fibre surfaces. Incomplete spreading of wax-like and oil-like finish components was found and there were particle-like clusters on the fibre surfaces. The waxy and oily components separated into two phases which were mapped by measuring adhesion forces. The finished regions had an average layer thickness of around 10nm and the contact angle with the polypropylene surface was about 10°. The measurements were mainly qualitative and although the distribution of two distinct finish components was mapped, no chemical information was provided. When the finish components are similar in physical characteristics (i.e. all oily or all waxy) and the main difference is in the chemistry of the components, scanning force microscopy may not be able to distinguish the location of finish constituents with the same degree of success. Furthermore, adsorbed films can be <50Å (5nm) thick (Schott, 1967, Tiberg and Landgren, 1993). This is less than the 10nm deposits measured in Leijala and Hautojärvi's work. For single close packed monolayers of surfactant molecules on a surface, layer heights can be less than 5Å (Schott, 1967, Shih *et al.*, 1993) and scanning force microscopy might struggle to define the location of the deposited layer.

There are problems with the finish analysis techniques described above. Extractions rely on the assumption that all of the finish is extracted. Components may, however, have differing solubilities so even when techniques are used that identify individual components, one cannot be sure that the composition of the extract is exactly the same as that of the finish on the fibres. When using tracers, it is assumed that the tracer distribution is the same as that of the finish. This requires intimate mixing. Finishes containing more than one component could give misleading results if the solubility, and hence amount of tracer dissolved, was different in the various components.

A method which permits analysis of finishes directly on fibres without extraction and without the need for tracers would be of great value and it would complement the other available techniques. Secondary Ion Mass Spectrometry (SIMS) may be such a suitable technique since it enables the chemical composition of surfaces to be deduced, and it should be possible, after appropriate calibration, to analyze directly the surface composition and distribution of multi-component finish systems on fibres. Also, SIMS is sensitive to deposit concentrations on surfaces of much less than a monolayer (Vickerman, 1989). It is for these reasons that the first part of this study examines the application of SIMS to the analysis of a fibre finish.

1.2 WET LUBRICATION IN FABRIC PROCESSING

The literature on this topic is sparse. A number of patents which relate to wet lubrication exist. These are not just for textile end uses but also cover food processing, plastic component manufacture and other industries. Reports do not explain how wet lubricants work. They tend to comment on performance, and list types of chemistry in common use. A summary of some of the available information is given in Table 1.1.

Table 1.1 Common Wet Lubricants and their Applications

Lubricant type	Use	Manufacturer	Inventor/Author	Reference
Aqueous wax dispersion	Dyebath	Sandoz	B Danner, F Palacin	GB 2282153, (1994)
Aqueous wax dispersion	Yarn	Sandoz	B Danner	US5389136, (1995)
Acrylic acid, amide, vinyl	Dyebath	Ciba-Geigy	M Kuhn, P Ouziel, H U Berendt	EP506613, US5399616 (1995)
Acrylamide/ acrylic acid	Dyebath	Ciba-Geigy	M Kuhn, P Ouziel	US5445655, (1995)
Graft polymer (PEG/fatty acid)	Dyebath	Ciba-Geigy	H Abel, P Schafer, H U Berendt	US4705525, (1987)
Neutralised fatty acid sulphate	Dyebath	*	Lloyd Barringer, Jr.	Am. Dyestuff Reporter, September (1994)
Sulphonated fatty ester	Dyebath	*	"	"
Fatty amide	Dyebath	*	"	"
Fatty acid ethoxylate	Dyebath	*	"	"
Polyacrylates	Dyebath	*	"	"
Acrylamide/ acrylic acid copolymer	Dyebath	*	"	"
Paraffinic hydrocarbon	Dyebath	*	Lloyd Barringer, Jr.	Am. Dyestuff Reporter, September (1994)
Modified polysiloxane	Dyebath	*	"	"
Polyacrylamide	Dyebath	*	"	"
Quaternary ammonium salts/fatty acid	Food conveyer belts	Ecolab Inc.	C T Liu, J C Dirksen	WO 9213048
N-fatty alkylalkylene di-amine acetate	Food conveyer belts	Ecolab Inc.	B E Schmidt, R E F Swerts	WO 9213050
PEG/lauric acid/triethanol-amine	Metal anti-wear	*	Y Wan, Q Xue, L Cao	Synth. Lubr., 13(4), 375-380, (1997)

Table 1.1 Continued

Lubricant type	Use	Manufacturer	Inventor/Author	Reference
Si oil/vegetable oil/wax/ surfactant	Metals	*	D L Moses	US5549836, (1996)
Fluoro surfactants & PTFE particles	General	Dainippon Ink & Chemicals	K Tanaka, Y Hashimoto	JP08151591, (1996)
Fatty alkylamino polyalkylamino carboxylic acid	Food conveyer belts	Henkel	B Winkelmann, W Luedecker	DE4412800, (1995)
Fatty acid amidoalkylen-aminocarboxylic acid	Food conveyer belts	Henkel	B Winkelmann, H Kluschanzoff	DE4406195, (1995)
Surfactants, mixed ethers, alkyl/alkenyl oligoglycosides	Food conveyer belts	Henkel	M Neuss, B Fabry	DE4419926, (1995)
Fatty amine	Food conveyer belts	Henkel	A Laufenberg, W Preibsch, K H Schmitz	WO9403562, (1994)
Amphoteric surfactant or salt	Heat transfer systems	Berol Nobel	M Hellsten, I Harwigsson	WO9511288, (1995)
Synthetic diamine, ethoxylated coco amine, fatty acid	Plastic stress cracks	Diversey Corp.	C E Rossio	WO9500608, (1995)
Fatty acid diamine salts, metal sulphonates	Plastic stress cracks	Ecolab Inc.	T A Gutzmann	WO9213049, (1992)
Aqueous wax dispersion	Auto sheet fabric finish	Kao Corp.	J Takahashi	JP05331766, (1993)
Acrylate polymers, Na stearate/oleate, POE condensate	Cable installation	Garware Wall R & D	R M Telong	IN170133, (1992)
Carbopol 940, fatty acid K soap, IPA, POE	Cable installation	American Polywater Corp.	N Jonnes	US4461712, (1984)

Table 1.1 Continued

Lubricant type	Use	Manufacturer	Inventor/Author	Reference
Octanoic/oleic acid soaps, anionic surfactant, sequesterant	Conveyers	Laporte Industries Ltd.	C Revell	WO9303125, (1993)
N-acyl sarcosinate/ alkyl taurate	Conveyers	W R Grace & Co.	T C Tesdahl, D L Holcer, H E Crotty	US3766068, (1973)
PTFE, inorganic fillers, nonionic surfactant	Tyre moulding	Mogul-Eurotherm	H Wagner	DE4107932, (1992)
Diorgano-siloxane, alkylene oxide polyol, solids	Tyre moulding	General Electric Corp.	F J Traver	DE2427029, (1975)
Fatty alkyl amines	Belt lubricant	Akzo	F Weber, W Preibsch	EP372628, (1990)
Guar compounds, methylgluceth-10, TiO_2	Shaving skin	White Laboratories Inc.	T Newberry Jr., R Uhrmacher, R Arblaster	US4585650, (1986)
Na/K salts of fatty acids, rape/castor oils	Machine oil	Mugijima Toru	*	JP59136395, (1984)
Salts of alpha-olefin maleic anhydride	Low foam lubricant	Mitsubishi	*	JP59100196, (1984)
40-50% alcohol in water	Metal antiwear	Inst. Mashinoved, Moscow	R M Matveevskii *et al.*	Trenie Iznos, 4(1), 68-73, (1983)
Non-linear alpha-olefin carboxylic acid alkanolamine salt	Low foam lubricant	Mitsubishi	*	JP57102996, (1982)
Polyoxyalkylene glycol, dipropylene glycol, solvent	General	Nippon Oils & Fats	*	JP5611296, (1981)
Monoalkyl phosphates, PEG monoalkyl phosphate esters	Package transportation	Diversey Wyandotte	*	JP58187495, (1983)

Table 1.1 Continued

Lubricant type	Use	Manufacturer	Inventor/Author	Reference
Napthenic oil, emulsifier/ dispersant, antiwear/rust agent	Hydraulic fluids	Mobil Oil Corp.	J Shim, D A Law	US4419251, (1983)
Polysiloxane, Na butyl napthalene sulphonate, alcohol	Cassette tapes	Tech. Bureau, Russia	V D Bosenko *et al.*	SU883159, (1981)
Vegetable/ mineral oil, inorganic fibres	Pipe installation	Tachibana Shokai Ltd.	*	JP56026994, (1981)
Alkanolamine salt, carboxylic acids & other components	General	Mobil Oil Corp.	R H Davis	US3769214, (1973)

The friction reducing capacity of wet lubricants in textile processing is an area where there appears to be little fundamental understanding and is an area for investigation.

1.3 FRICTION

Friction is an important parameter in textile processing. Control of friction in carding, drafting and spinning is essential in order to produce good quality yarns with minimal faults. Other factors such as fibre crimp and dimensions are also important (Röder, 1955).

Too high or too low friction between fibres or between fibres and machinery surfaces causes problems such as card loading, weak yarns and frequent yarn breaks (Billica 1977, 1984a, Becker, 1993, Broughton Jr. and El Mogahzy, 1993). Inter-fibre friction has been shown to be a dominant factor in determining the tensile strength of yarns (Broughton Jr, *et al.*, 1992).

1.3.1 Basic Laws of Friction

There are two basic laws of friction. Consider the object sliding along a surface in Figure 1.1. Friction opposes the force F, which moves the object forwards. The block in this example has faces which have different areas. It makes no difference which face the block rests on, as the first law states that the friction is independent of the area of contact.

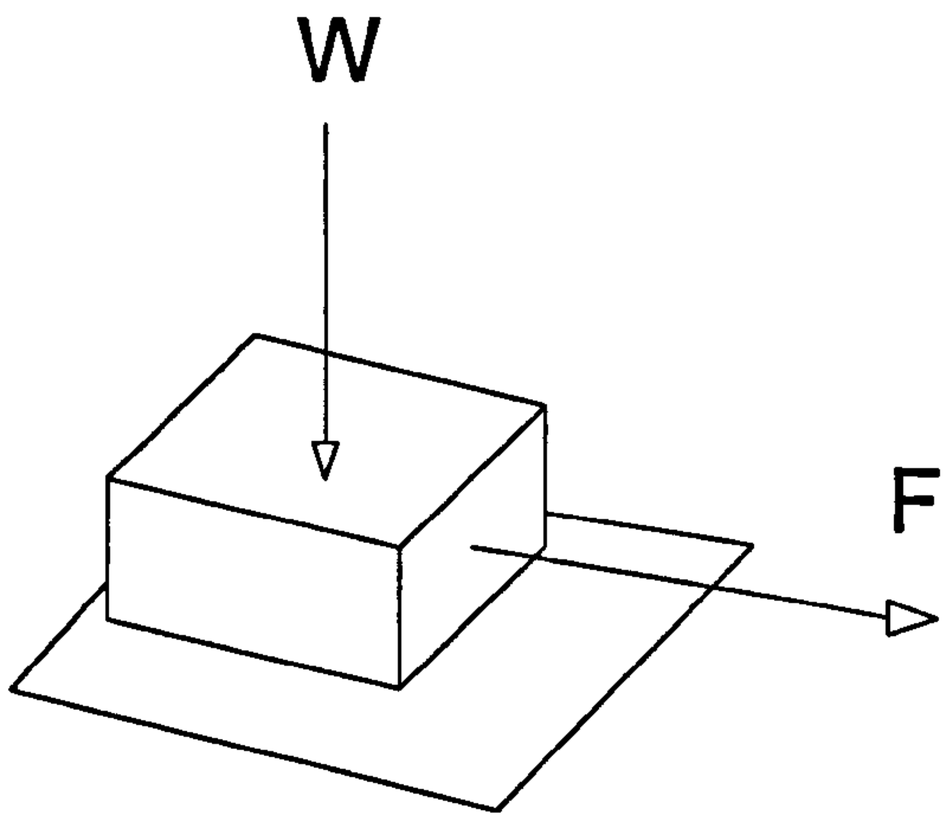


Figure 1.1 An Object Sliding on a Surface Subject to the Basic Laws of Friction

The second law states that the friction is proportional to the load, W. This means that the ratio of friction/load is constant. This constant is called the coefficient of friction μ. The friction force is equal and opposite to F, hence the relationship can be written

$$F = \mu W.$$

These laws were first observed by Leonardo Da Vinci. They were rediscovered later, in the early 1700's, by the French engineer Amontons and the above expression is sometimes known as Amontons' law. Later in 1781 Coulomb verified these laws and

observed that kinetic friction could be significantly lower than static friction (Bowden and Tabor, 1956).

On a microscopic scale, surfaces in contact are rarely smooth, and when they move, asperities either slide over each other, or junctions are sheared. Bowden and Tabor (1950a), described an adhesion-shearing mechanism and they gave the frictional force F as the product of the true area of contact A and the shear strength of the junctions S, i.e.

$$F = AS$$

or in terms of the friction coefficient

$$\mu = F/W = S/P,$$

where P is the yield pressure of the material at the junctions. The relationship between shear strength, yield pressure and friction coefficient holds to a first approximation for clean metals. In practice, agreement with the model may be markedly affected by small amounts of surface contamination.

Amontons' law describes reasonably well the sliding of clean metal surfaces over each other. However, for other materials which have different elastic and plastic deformation characteristics, and may be contaminated, the laws do not apply. This is particularly the case with textiles where at least one of the surfaces is polymeric and lubricants and antistat are normally present.

1.3.2 Friction of Textiles

Numerous attempts have been made to describe textile friction more precisely than does Amontons' law. A variety of experimental techniques have been used, such as the rotating pin method (Buckle and Pollitt, 1948, Röder, 1953), the twist method (Lindberg and Gralen, 1948), an inclined plane slider (Kalyanaraman and Praksam, 1987) and pulling fibre assemblies apart (Lord, 1955, El Mogahzy and Broughton, 1993). The results from the literature demonstrate that since Amontons' law does not apply generally to textiles, there are several additional factors that must be taken into account when studying fibre, yarn and fabric friction.

Howell (1951) gave equations for fibre friction of the form

$$F = \mu_0 R + F_0$$

and

$$\mu = \mu_0 + aA/R$$

where F is the friction force, μ is the friction coefficient, R is the normal force, A is the contact area and F_0, μ_0 and *a* are constants. Howell gave values of μ_0 and F_0 for a selection of fibres. These are shown in Table 1.2.

Table 1.2 Howell's Values of μ_0 and F_0

Fibre type	μ_0	F_0
Nylon	0.26	1.5
Viscose	0.3	0.4
Cuprammonium	0.32	1.1
Acetate	0.39	0.8

Howell proposed that Hertz's equation could be used to predict friction such that

$$F = \sigma S[a(R/E)^{2/3} + kA_0]$$

where σ is a constant corresponding to cohesion, S is the shear strength of the bulk material, *a* is a geometric constant, E is Young's modulus, k is a smoothness factor and A_0 is the apparent contact area.

An expression given by Makinson (1952) attempts better to describe textile friction:

$$F = a+bW^n$$

where *a* and *b* are suitable constants and n<1. This suggests that the friction is finite when the normal load W is zero. Hence the relationship

$$F = kW^n$$

is preferred where k is a suitable constant. This general equation has been suggested by several workers (Guthrie and Oliver, 1952, Howell and Mazur, 1953, Lord, 1955, Viswanathan, 1966, Gupta and El Mogahzy, 1991, El Mogahzy and Broughton, 1993). The index n is unity for materials which exhibit purely plastic deformation and this transforms the above expression to Amontons' law. For materials which exhibit purely elastic deformation n = 2/3.

Gralen (1952) used the twist method to produce friction data for Terylene fibres. He fitted an equation to the data of the form

$$F/W = a + bW^{\alpha}$$

where F is the friction force, W is the normal load and a,b and α are constants. When b = 0 the equation gives Amontons' law. When a = 0, the expression takes the form

$$F = bW^{(1-\alpha)}.$$

Lord (1955) pulled apart fringes of cotton fibres compressed under known loads. By measuring the force required to separate the fringes the values of n and k (in the equation $F=kW^n$) could be calculated. Lord showed that Karnak and Texas cotton varieties had different k constants. The equations derived were

$$F = 0.468\ R^{0.886}\ \text{(Karnak)}$$

and

$$F = 0.521\ R^{0.886}\ \text{(Texas)}.$$

Here, R is the normal force. Lord's results suggest that the behaviour of cotton is neither purely elastic nor purely plastic but somewhere in between.

El Mogahzy and Broughton (1993) give values of k and n for Acala and California cotton. A similar method to Lord's was used i.e. pulling apart fringes of fibres. Even so, n and k were quite different to Lord's values. El Mogahzy and Broughton's constants give equations of the form

$$F = 2.25\ R^{0.641}\ \text{(Acala)}$$

and

$$F = 1.84\ R^{0.675}\ \text{(California)}.$$

El Mogahzy and Broughton developed the theoretical formula

$$F = SC_M(1/K)^n m^{1-n} R^n$$

where S is the bulk specific shear strength, C_M is a constant that depends on the distribution of applied load, m is the number of asperities in contact and K indicates the hardness of the junctions in contact. This is of course equivalent to $F=kW^n$, with $k = SC_M(1/K)^n m^{1-n}$ and the normal force written as R instead of W.

Howell and Mazur (1953) used the expression

$$F = aR^n$$

to describe friction of man made fibres, where a and n are the friction indices.

The friction force F has already been equated to the shear strength of the material S, multiplied by the actual contact area A (i.e. F = SA).

In the case of plastic materials

$$A = R/p_y$$

where p_y is the yield pressure of the material and R is the normal load. This is not appropriate for textiles where elasticity is present. Howell and Mazur (1953) proposed that

$$A \propto R^k$$

where k is an area index. For ideal elasticity k = 0.67. Howell and Mazur give n, *a* ($F=aR^n$) and k for various fibres. Their results are summarized in Table 1.3. Friction measurements were made using an inclined plane and contact area vs load relationships were developed using an interference method.

Table 1.3 Summary of Howell and Mazur's Friction Constants For Man-Made Fibres

Material	n	*a*	k
Cellulose acetate	0.96	0.6	0.75
Viscose rayon	0.91	0.49	0.73
Drawn nylon	0.8	0.92	0.72
Undrawn nylon	0.9	0.85	0.73

It was proposed that the coefficient of friction μ could be defined as

$$\mu = a/R^{1-n}.$$

Following on from this work Mazur (1955) showed that when the inclined plane method was used, there were significant differences in friction between A-B and B-A contacts for dissimilar fibres A and B. This was probably because the upper filament suffered continual rubbing at a particular point whereas the lower filament was traversed along its whole length. Therefore the conditions at the two surfaces were not identical.

Viswanathan (1966) examined the inter-fibre friction forces of cotton and several man-made fibres under normal loads between 30g and 298g and at 2mm/s sliding speed. Values of n and *a* were found from the relationship $F=aR^n$. Viswanathan suggested that the two parameters were interdependent and devised the expressions

$$a = 8.7971 - 10.2766n$$

for a range of cottons, and

$$a = 5.6047 - 6.0663n$$

for regenerated fibres.

Du Bois (1966) discussed earlier work, which gave similar relationships to those shown by Viswanathan. Du Bois went on to study cotton, viscose, acetate, cuprammonium rayon, wool, nylon, polyacrylonitrile, Terylene and Dynel fibres. The following equations for friction force F and friction coefficient μ were obtained,

$$F = (3.855 - 3.58n)R^n$$

and

$$\mu = (3.855 - 3.58n)R^{n-1}.$$

Guthrie and Oliver (1952) examined the inter-fibre friction of viscose using a stick-slip method. Experimental data were fitted to the $F=kW^n$ relationship. They showed that 1.5 and 3 denier fibres were mostly plastic in their behaviour (n approaching 1) whilst 4.5 and 8 denier fibres were mostly elastic (n approaching 2/3). Surprisingly, neither inclusion of titanium dioxide delustrant nor dyeing the fibres was found to have a major effect on the measured friction. In general the static friction force was higher on finished fibres than on extracted fibres. The kinetic friction of finished and unfinished fibres was generally lower than the corresponding static friction.

Gupta and El Mogahzy (1991) proposed that the morphology of the contacts and mechanical properties of the junctions determine friction. Hence friction is a function of the number of asperity contacts and their area. They continued by describing a general pressure vs contact area relationship of the form

$$P = KA^{\alpha}$$

where P is the pressure, A is the area of contact and K and α are constants that can be considered as hardness and shape factors respectively.

A general relationship between coefficient of friction and sliding speed, lubricant viscosity and pressure was shown by Olsen (1969). Three regions were identified (see Figure 1.2). At low speed, low viscosity and high pressure, boundary friction occurs. Lubrication is best performed by solid monolayers.

At the other extreme, the hydrodynamic region occurs at high speed, high viscosity and low pressure. Friction is developed by the shear stress, which takes place in the liquid lubricant film separating the rubbing surfaces.

In between the extremes is the semi-boundary region, which represents the transition between the two mechanisms. It is here that the minimum friction coefficient is realized.

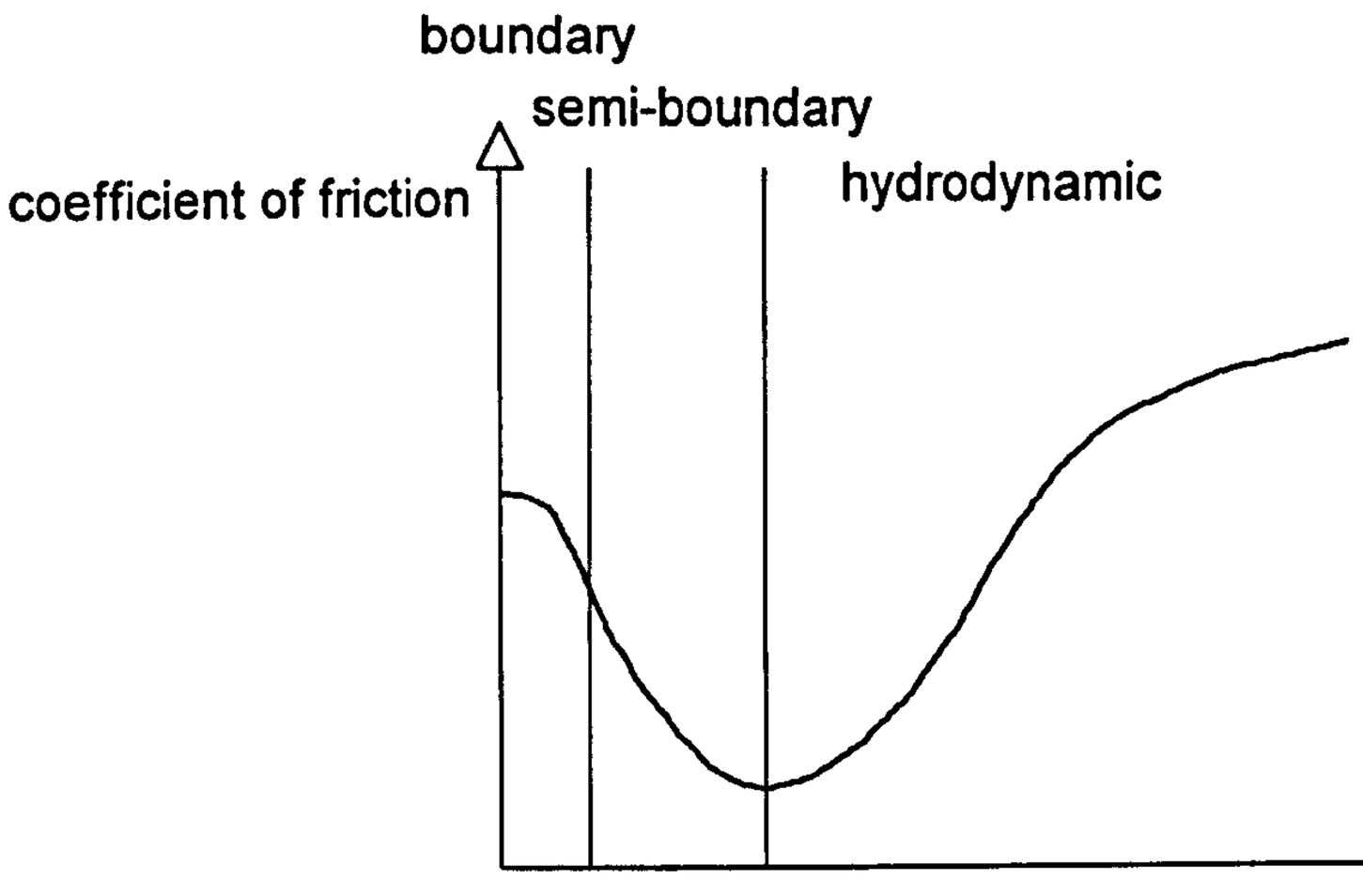


Figure 1.2 General Friction Behaviour of Lubricated Textile Yarns

Schick (1973a) also presents the general friction curve. He assigns speed ranges to the three regions. In Schick's experiments boundary friction was thought to occur between 10^{-4} to 10^{-1} m/min, semi boundary friction between 10^{-1} to 5 m/min and hydrodynamic friction above 5m/min.

In the boundary region surface asperities are in contact. In the hydrodynamic situation the surfaces are separated by a continuous fluid film. In the semi-boundary region intermittent contacts occur which give rise to stick/slip behaviour. Under hydrodynamic conditions Schick proposed that increasing surface roughness reduces friction. Smoother fibres would produce larger true contact areas since there are fewer asperities per unit area of fibre surface. A larger true contact area would increase the friction force, assuming the shear strength of the asperity junctions remains constant. This is why friction increases with fibre lustre, i.e. bright fibres have higher friction than dull ones. The surface of bright fibres is considered smoother than dull fibres, the dull ones containing TiO_2 delustrant.

Under the same load, increasing the fibre roughness would cause the pressure to increase (since the contact area between rough surfaces is smaller than for smooth ones). The overall effect would be to shift the mechanism towards the semi-boundary region, hence reducing friction. In the boundary region increasing surface roughness increases friction and wear. Schick suggested that the friction observed is independent of whether the metal guide or fibre surfaces contribute to the roughness.

Schick (1973d) continued his observations using nylon, polypropylene and polyester yarns. Wetting of the yarns by the lubricant was found to be important. With good wetting Schick found that friction was independent of lubricant viscosity in the boundary region but highly dependent on viscosity in the hydrodynamic region. When poor wetting occurred there was no dependence of friction on lubricant viscosity in the hydrodynamic region. This was thought to be because poor wetting of the sliding surfaces prevents the formation of a continuous fluid film. Hence a requirement of the lubricant is that its surface tension is below the critical surface tension of the substrate. Schick also found that the minimum friction was obtained when the quantity of finish on the yarns was 0.15%. The friction reached a plateau with increasing finish level at 0.5%.

Sinha (1977) reviewed Olsen and Schick's work and drew some general conclusions. Points relevant to this work are as follows. (i) In the hydrodynamic region an increase in the guide surface roughness is analogous to a pressure increase between the fibre and the guide. This is a result of the decrease in fibre/metal contact area and results in a shift towards the semi-boundary region with a consequent lowering of friction. (ii) Stick/slip decreases with increasing speed in the semi-boundary region and disappears abruptly in the transition to hydrodynamic friction. Stick/slip increases with increasing pre-tension (pin

method). (iii) Heat stable lubricants show a continuous decrease in friction with increasing temperature. Unstable lubricants show an initial decrease, pass through a minimum and then show a rise in friction with increasing temperature. (iv) Increasing the area of contact increases friction. The area can be increased by larger wrap angles (pin method), increased pre-tension or higher denier fibres or yarns. (v) In the boundary region friction increases with lustre. In the hydrodynamic region the reverse occurs. (vi) Boundary friction, against surfaces of higher shear strength, is controlled by the shear strength of the fibre (i.e. the weaker material).

Schick (1975) also gives a detailed account of the effects of load, speed, roughness, temperature, contact area, yarn twist, guide diameter, tension, regain, material type, electrostatic charge, wetting behaviour, lubricant viscosity and level of finish on friction.

The studies of textile friction, described so far, deal mainly with fibres and yarns. Wilson (1963) considered the friction of fabric on fabric. The friction force (F) was found to be related to pressure (P) by an expression of the form

$$\log F = C + n \log P$$

where the values of n and C depend on the structure of the yarns in the fabric, the chemical nature of the fibres and the finish applied. Wilson determined values of n in the range 0.57 to 1.06 and C in the range –0.74 and 0.55. In later work by Carr *et al.* (1988) the friction of fabrics containing cotton, polyester and wool was considered, with reference to Wilson's earlier study. Amontons' law was said to be invalid and Wilson's equation was verified. Carr and co-workers determined n and C for both static and dynamic friction.

Both sets of n and C values were in broad agreement with Wilson's results and the ranges of n and C for static friction were not dissimilar to those of dynamic friction. Table 1.4 summarises Carr and co-workers' results.

Table 1.4 Ranges of n and C for Fabric on Fabric Friction Determined by Carr *et al.*

Friction	n	C
Static	0.73 to 0.97	-0.37 to 0.83
Dynamic	0.67 to 0.94	-0.33 to 0.80

Yoon *et al.* (1984) measured the friction of knitted cotton, polyester and cotton polyester blend fabrics against the fabrics themselves and against rubber. Static and kinematic friction coefficients of cotton against cotton were given as 2.3 and 2.0 respectively. The kinematic friction coefficient of cotton against rubber was 1.6. When polyester fabric was wetted the friction coefficient against rubber was as high as 9.0, compared to the dry polyester/rubber friction coefficient of 2.9. Yoon and co-workers presumed that the high wet friction coefficient was due to a water film which formed between the contact surfaces, and that the surface tension of the water provided an additional resistance to sliding.

Zurek *et al.* (1985) measured fabric/fabric friction of viscose, acetate and nylon in plain and sateen weaves. For viscose plain weave fabric the static and kinetic friction coefficients were in the ranges 0.3 to 1.2 (static) and 0.3 to 0.9 (kinetic). Yarn/yarn friction of threads pulled from the fabric had friction coefficients of 0.15 to 0.45 (static) and 0.15 to 0.35 (dynamic). The friction coefficient of the fabric/fabric contact was dependent on the

direction of warps and wefts when sliding and on the normal load. Overall, the friction coefficients of yarn/yarn contact are lower than those of fabric/fabric. This is probably due to additional resistance produced by interlocking of the high and low points of the weave.

Ajayi *et al.* (1995) noted that the difference between static and kinetic, fabric/fabric friction forces (F_s and F_k) decreased with washing. This produced harder and rougher fabrics. In a subjective assessment, roughness decreased with both F_s and F_k. In later work, Ajayi and Elder (1997) found that more compressible fabrics exhibited larger differences between F_s and F_k. More compressible fabrics were also described as softer. Kinetic friction coefficients for cotton on cotton fabrics were given in the ranges 0.56 to 2.28 (woven) and 0.70 to 3.40 (knitted). As in the work of Zurek *et al.* (1985), the actual friction coefficient depended on the direction of sliding and on the normal load.

Finally, Virto and Naik (1997) gave friction coefficients of a knitted cotton fabric against steel, nylon and rubber surfaces, at speeds of 0.3334 mm s^{-1} and 1.667 mm s^{-1}, and pressures between 2 kPa and 15 kPa. The order of friction coefficients (μ) for the various sled materials was μ_{steel} (~0.20 to 0.25) < μ_{nylon} (~0.30 to 0.35) < μ_{rubber} (~0.40 to 0.45). The friction coefficient had little dependence on fabric structure, but was strongly dependent on the Young's modulus and Poisson coefficient of the sled material. Harder materials probably form and break fewer micro-contact bonds with the fabric, per unit area of surface, leading to smaller sliding forces. This might explain why Virto and Naik observed the above trend.

1.3.3 Boundary Friction in Textiles

The work described in the previous section provides some general expressions and relationships between textile friction and the conditions under which sliding occurs. Boundary friction occurs at low speeds where surface asperities are in contact and are forced to slide over each other or shear. Schick (1973a) suggested that speeds of 10^{-4} to 10^{-1} m/min were appropriate for boundary friction in his experiments.

Fort Jr. and Olsen (1961) examined the boundary friction of various textile yarns using the pin method. They showed that the boundary friction of clean fibres against other clean solid surfaces was dependent on fibre type but independent of the other surface. Their results are summarised in Figure 1.3.

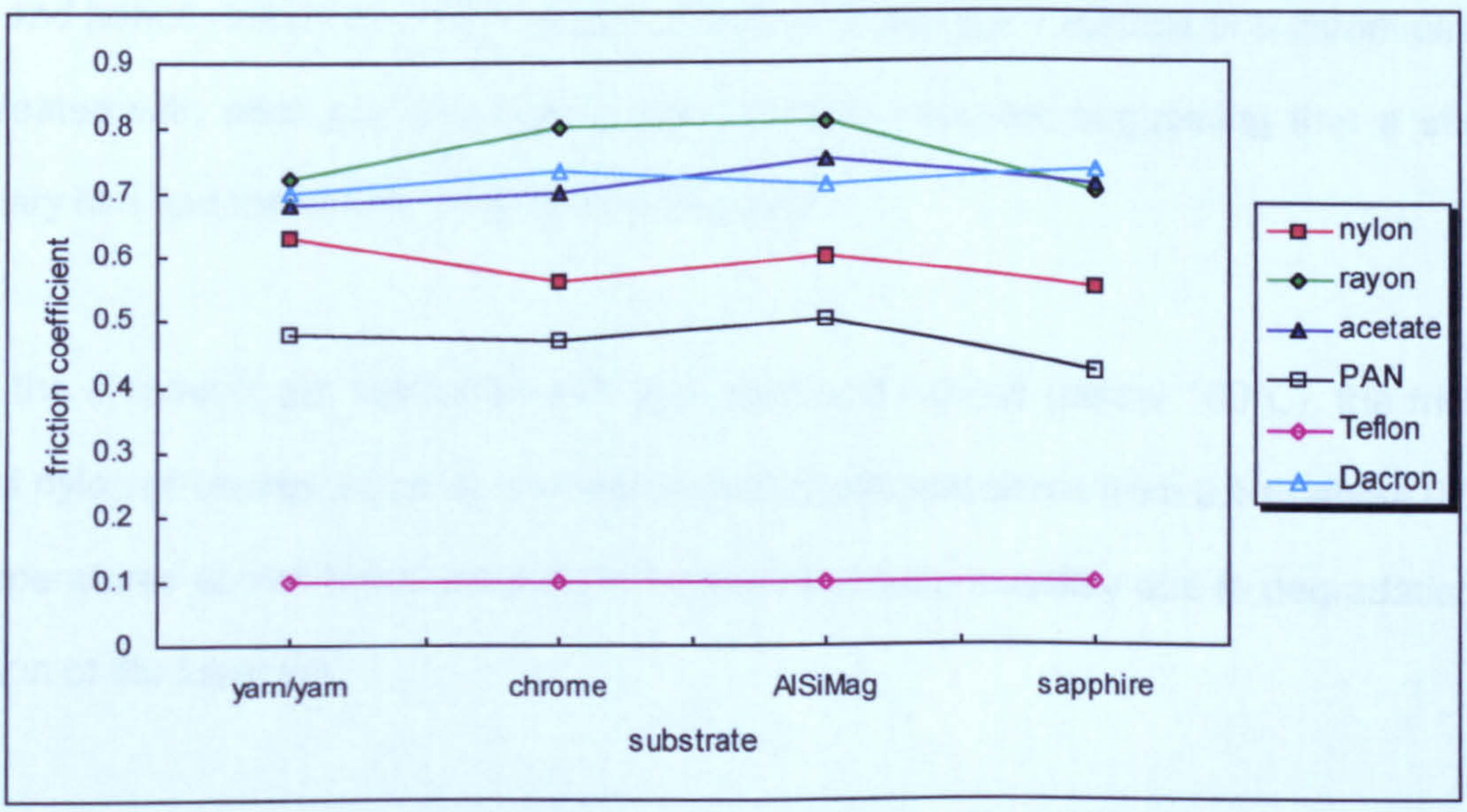


Figure 1.3 Fort Jr. and Olsen's Boundary Friction Results

It was suggested that the low friction of Teflon is due to shearing taking place at the interfacial contact points rather than in the bulk structure which is characteristic of other polymers in the non-lubricated state.

Mineral oil and oleic acid were shown to be ineffective fibre/fibre boundary lubricants on Dacron (polyester), acetate, rayon and polyacrylonitrile fibres. Stearic acid and n-octadecylamine reduced boundary friction. Polyacrylic acid grafted to nylon and treated with n-octadecylamine also gave low boundary friction. Fort Jr. and Olsen suggested that physically adsorbed molecules, lying flat on the fibre surfaces are poor boundary lubricants. The adsorbed layer is easily penetrated and the friction would not be very different to that of non-lubricated fibre. Chemisorbed and close packed monolayers (e.g. n-octadecylamine on grafted nylon and stearic acid on other fibres) will support larger loads and hence reduce boundary friction effectively. When the surface of a chromium pin was treated with oleic acid low friction against fibres resulted, suggesting that a strong boundary film had formed on the chromium surface.

When the chromium pin lubricated with oleic acid was heated (below 160°C), the friction against nylon or Dacron yarns decreased (friction coefficient drops from 0.1 to about 0.03). At temperatures above 160°C the friction increased sharply possibly due to degradation or oxidation of the lubricant.

Schick (1974) has considered the effect of roughness on boundary friction of textiles. He concluded that friction increases with fibre lustre, i.e. bright fibres have higher friction than dull ones. The surface of bright fibres is considered smoother than dull fibres, the dull ones containing more TiO_2 delustrant. Schick's conclusion is not surprising, since

smoother fibres would produce larger true contact areas since there are fewer asperities per unit area of fibre surface. A larger true contact area would increase the friction force, assuming the shear strength of the asperity junctions remains constant. Schick confirms Fort Jr. and Olsen's observation that boundary friction of clean fibres against other solid surfaces is independent of the guide material provided the shear strength is equal to or greater than the fibres. The magnitude of the boundary friction was demonstrated to be controlled by the shear strength of the fibre.

Tabor (1960) considered the friction of polymers and fibres. Experiments with crossed cylinders of nylon gave the area of contact A as

$$A = cW^{0.74}D^{0.52}$$

where W is the load, D is the diameter of the cylinders and c is a strength factor of the material. Since the friction force F is the product of the real area of contact and the specific shear strength of the interface (F=AS), F can be expressed as

$$F = ScW^{0.74}D^{0.52}$$

and the coefficient of friction μ becomes

$$\mu = ScW^{-0.26}D^{0.52}.$$

Tabor suggested that when clean surfaces slide over each other, S is essentially the bulk shear strength of the polymer. Soft polymers would have a large value of A but S would

be small. With hard polymers A would be small but S would be large. As a result there should be little difference in friction between hard and soft polymers, which is indeed the case. The exception to this is PTFE in which adhesion between molecules is small (S small), but the molecules are rigid so A is also small. Hence friction is very low.

Tabor also concluded that lubricants have little effect on the boundary friction of polymers. This is because the shear strength of the lubricant film cannot be greatly different from the polymer itself. Using octacosanoic acid ($C_{27}H_{55}COOH$) as a lubricant, nylon on nylon fibres had non-lubricated and lubricated friction coefficients of 0.8 and 0.6 respectively. Adding the same lubricant to bulk nylon only reduced the friction coefficient from 0.4 to 0.3. In contrast, lubricants on metals can reduce friction by a factor of 10 or more (e.g. on copper μ can be reduced from 1 to 0.05 or 0.1). The shear strength of the lubricant film is considerably less than the underlying metal, hence friction is reduced. Also, long-chain polar lubricant molecules find relatively few polar sites to adsorb on a polymer surface, so little protection is provided. On a metal surface a close packed layer of adsorbed lubricant provides effective lubrication.

Rubenstein (1963) studied the friction of cotton and nylon yarns lubricated by various waxy or oily materials. He suggested that in addition to the accepted mechanism of boundary lubrication, where lubricant molecules adsorb to the sliding surfaces and reduce adhesive forces, another mechanism might occur. If materials are permeable to lubricant molecules, they may penetrate amorphous regions of the polymer, rupturing weak bonds and altering the mechanical properties of the polymer. This is plasticisation. Rubenstein continued by proposing that the friction index n (n=1 for plastic materials) depends on the

lubricant applied. He used the capstan method (see section 1.3.7) to measure yarn friction and gave the expression

$$\mu_N \alpha (S_1/b^m)\omega^t(\rho/T_1)^q$$

where μ_N is the coefficient of friction, S_1 is the shear strength of the material in contact with the friction pin, b is the material modulus, ω is a roughness factor, ρ is the radius of curvature of the friction pin, T_1 is the initial tension and m,t,q are related indices all less than unity.

Rubenstein noted that as the carbon chain length of the lubricant increases, friction is lowered and hence surface damage is reduced, however longer chains do not penetrate the polymer so easily and the softening effect is reduced. As a general observation, Rubenstein stated that greater quantities of short chain lubricants are required for efficient lubrication than are necessary with longer chain homologues.

1.3.4 Hydrodynamic Friction in Textiles

In Schick's work (1973a) surfaces sliding over each other at speeds of 5 m/min or above, with a continuous fluid film between them were considered to be in the hydrodynamic region. Tabor (1960) proposed that in the hydrodynamic lubrication region the effective coefficient of friction is a function of ZV/W, where Z is the lubricant viscosity, V is the speed and W is the normal load. Figure 1.4 shows the trend suggested by Tabor.

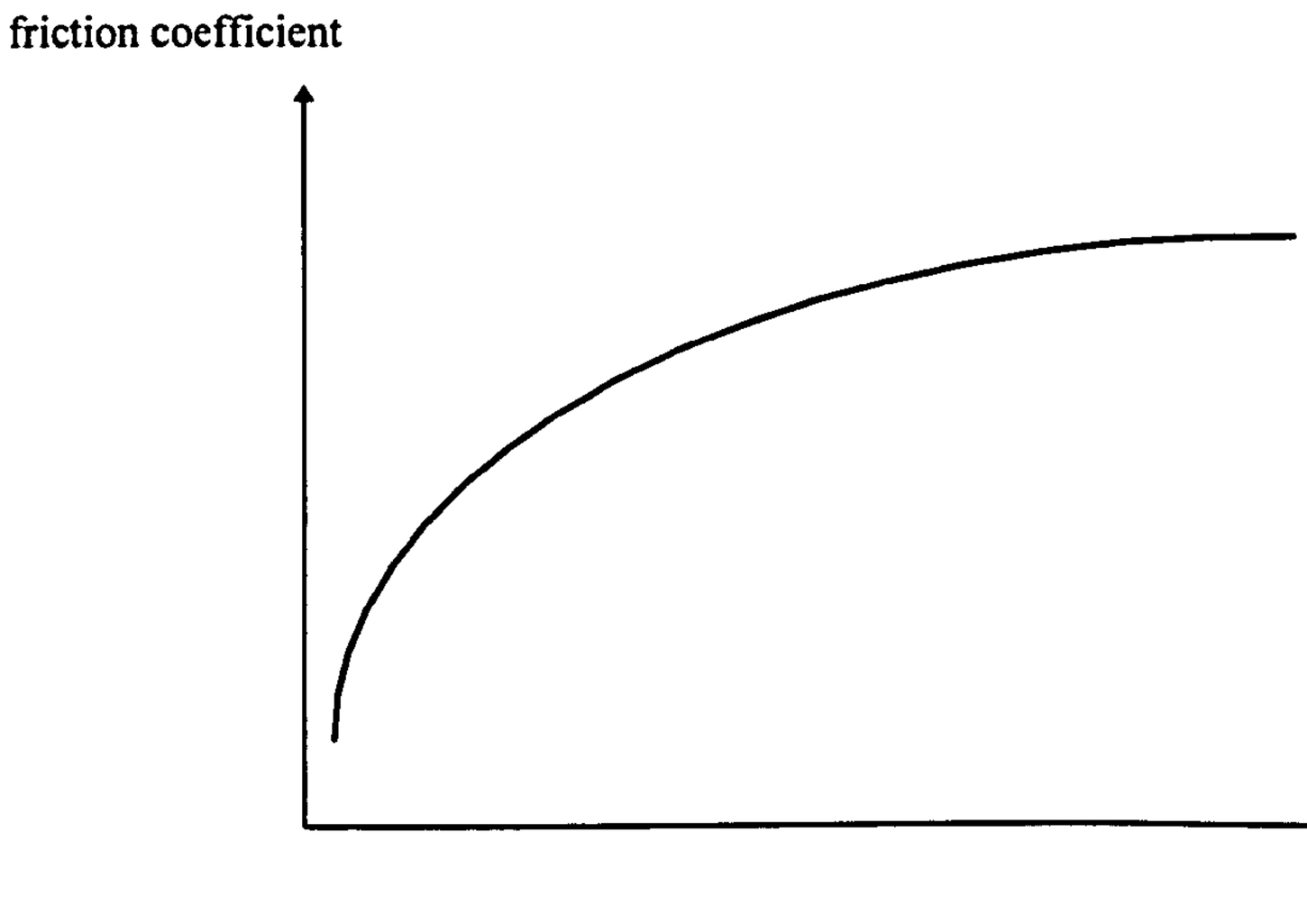


Figure 1.4 General Relationship Between Friction and ZV/W Shown by Tabor

Figure 1.4 should be compared with the curve showing the frictional behaviour of liquid lubricated yarns given by Olsen (1969) (Figure 1.2).

Tabor suggested that the wetting behaviour of the lubricant may also be important. This would influence the way in which the lubricant film forms between the two surfaces. It is reasonable to conclude therefore that good wetting is desirable.

Hansen and Tabor (1957) studied hydrodynamic factors in the friction of fibres and yarns using the pin method with a 180° wrap angle (see section 1.3.7). They produced the expression

$$\mu = (T - T_0)/(T + T_0)$$

where μ is the effective coefficient of friction and T and T_0 are final and initial tensions in the yarn or fibre. It was found that the friction coefficient depended on the lubricant viscosity, Z, the velocity between the fibre or yarn and the pin, V, and the load, W, with which the fibre or yarn presses against the pin. The measured results fitted an equation of the type

$$\mu = k(ZVr/W)^{1/n}$$

where k is assumed to be a constant, r is the friction pin radius and the value of n is between 4 and 5.

Schick (1973b) examined the hydrodynamic friction of nylon and polyester yarns, lubricated with preparations having viscosities in the range 56 to 5830 cps. He found the relationship

$$\mu = A \log\eta + B$$

where μ is the friction coefficient, η is the viscosity and A and B are constants. B corresponds to the theoretical friction coefficient at a viscosity of 1cps. Plots of μ vs logη for the two fibre types did not coincide. This suggests that other factors must be taken into account such as differences in wetting of the two fibres by the lubricants.

In further work Schick (1973c) found that fibres prepared with non-volatile lubricants show a continuous decrease in hydrodynamic friction with temperature, presumably because the viscosity decreases. Volatile lubricants show an initial decrease followed by a rise in

friction. This was attributed to volatilization of the lubricant and softening of the fibre polymer. Schick gave the equation

$$F = \eta(AV/d)$$

where F is the frictional force, η is the lubricant viscosity, A is the area of contact, V is the yarn speed and d is thickness of the lubricant film. It was shown that when the relative humidity was increased from 12% to 69%, the hydrodynamic friction of rayon was increased markedly. Such behaviour was attributed to swelling and hence increased area of contact at the fibre/metal pin interface. Schick also showed that increasing the angle of contact (pin method), increasing pre-tension and increasing denier all increased friction through an increase in contact area.

Park, Seefried and Bryant (1974) lubricated polyester, nylon and polypropylene yarns with polyethylene oxide/polypropylene oxide random copolymers of various molecular weights. They found that fibre/metal friction depended on sliding velocity. Friction maxima were observed with these lubricants at particular speeds depending on the molecular weight. The maxima occurred in the approximate range 1 to 100m min^{-1}. Park *et al.* fitted their results to the relationship

$$F = k(\eta U)^{1/n}$$

where k and n are constants, η is the lubricant viscosity and U is the sliding speed. The value of k was in the range 11 to 28 depending on yarn type, whilst n was between 2.4 and 2.6.

Billica (1977, 1984a) considered the cohesive force between two fibre filaments separated by a fluid lubricant film. Figure 1.5 shows the situation.

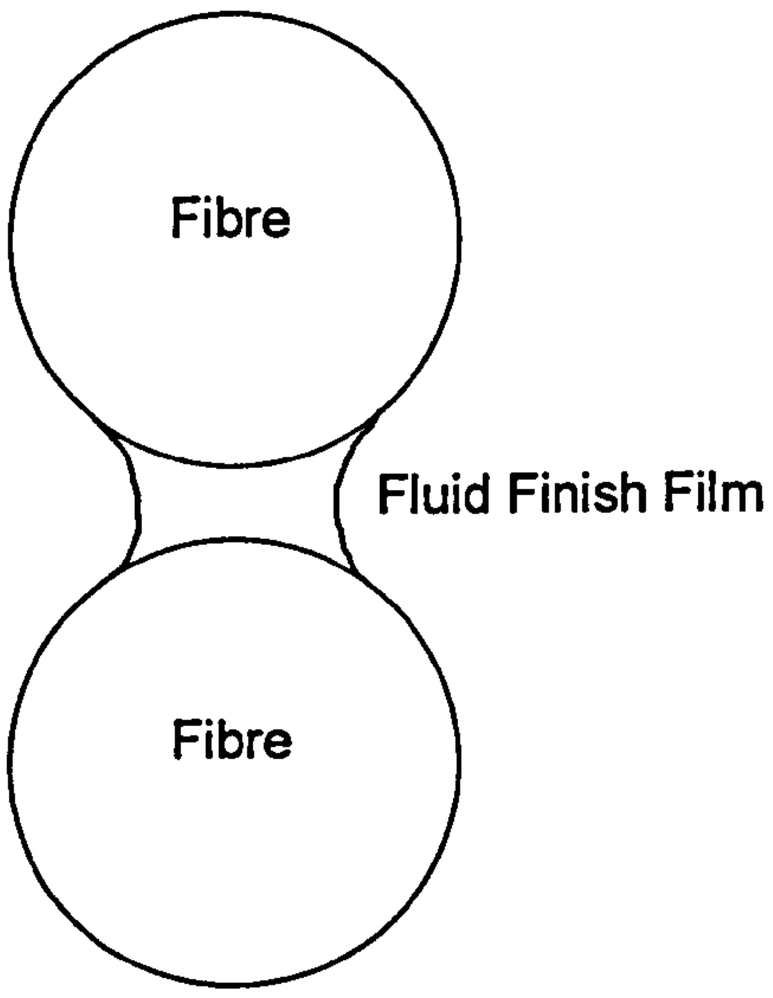


Figure 1.5 Two Fibres Separated by a Fluid Finish Film

An equation for the cohesive force F was given such that

$$F = \eta L(W/D)^3 \, dD/dt + 2L\gamma(1+ W/D)$$

where η is the finish viscosity, L is the length along filaments, W is the width of finish film, D is the inter-filament distance, t is the time for separation, and γ is the finish surface

tension. Whilst this may not relate to hydrodynamic friction when the speed of separation is low, cohesive forces are still important in fibre processing e.g. in carding, drafting and spinning.

1.3.5 The Effect of Moisture on Textile Friction

Wood (1952) studied the dynamic friction of viscose fibres by pulling filaments from bundles. He considered the effects of load, velocity, position in the bundle and humidity. It was found, via a factorial experiment, that the variables do not interact and that velocity, load and humidity were the most important parameters. An expression was given relating the friction force F and the velocity V such that

$$1000\,F = 3.2 + 0.198\,V + 0.014\,V^2.$$

The coefficients of variation in Wood's experiments were high and in the range 35% to 41%. In a later paper (1954) Wood found the relationship

$$10^4\,F = 0.89\,H + 246$$

where F is the friction force in grams and H is the per cent relative humidity. Again the coefficients of variation were high (31% to 42%). Wood suggested that as the relative humidity increases, the modulus of viscose decreases. According to King (1950) the area of contact is proportional to $(1/E)^{2/3}$ where E is Young's modulus. Consequently when moisture is adsorbed the contact area at a given load increases and so friction also increases.

An increase in friction with increasing regain was observed by Morrow (1959), who made measurements on cotton yarns. Measurements were made at a speed of 65 yd/min and at 20 to 21°C. A relationship was observed when friction was correlated with % regain (Figure 1.6). Morrow's results can be expressed as

$$\mu = 9.1x10^{-3}R + 0.219$$

where μ is the coefficient of friction and R is the % regain.

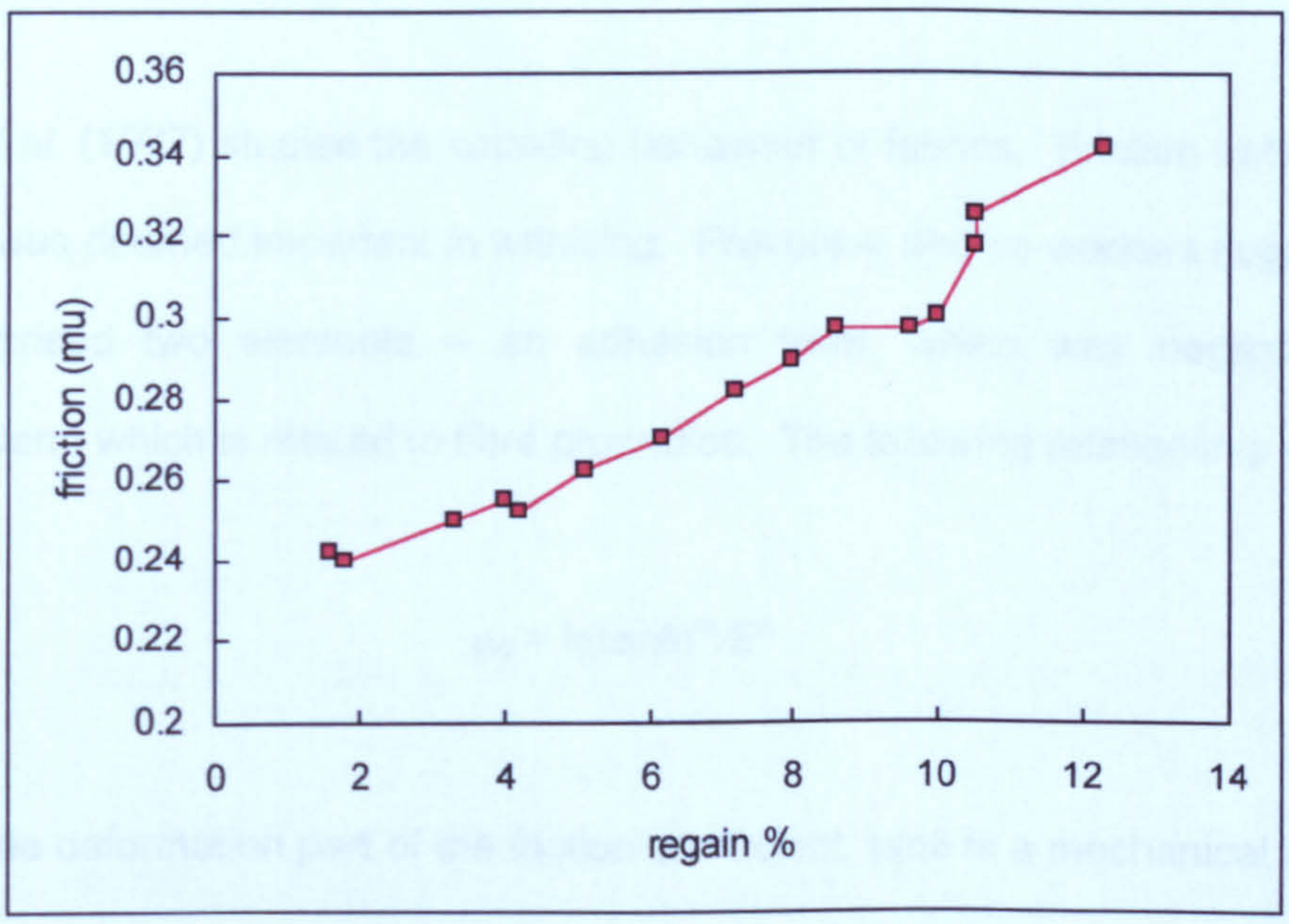


Figure 1.6 Morrow's Friction versus Regain Data for Cotton Yarn Against Steel

El Mogahzy and Gupta (1993) showed that wetting yarns increases friction. This is surprising for polypropylene and acrylic materials which are normally considered hydrophobic. A possible explanation was that water penetrated the interstitial spaces

between fibres in the yarns resulting in increased contact area. El Mogahzy and Gupta's wet and dry values of friction coefficient μ are shown in Table 1.5.

Table 1.5 El Mogahzy & Gupta's Dry and Wet Friction Coefficients

Yarn type	μ_{dry}	μ_{wet}
Polypropylene	0.287	0.343
Acrylic	0.190	0.225

Prevorsek *et al.* (1977) studied the wrinkling behaviour of fabrics. Friction between yarns in the fabric was deemed important in wrinkling. Prevorsek and co-workers suggested that friction comprised two elements – an adhesion term, which was negligible and a deformation term which is related to fibre properties. The following relationship was given

$$\mu_d = k(\tan\delta)^m/E^n$$

where μ_d is the deformation part of the friction coefficient, $\tan\delta$ is a mechanical loss factor, E is the fibre modulus, m and n are constants and k is assumed to be a constant. The equation suggests that friction would increase if the fibre modulus decreased. For a number of fibre types the tensile modulus decreases when wet (Morton and Hearle, 1993a). Hence the observed increase in friction as the moisture level of fibres increases is not surprising, however the variation of $\tan\delta$ with moisture content should also be considered.

1.3.6 The Effect of Cross Section Shape and Molecular Orientation on Textile Friction

El Mogahzy and Gupta (1993) used point and line contact methods to determine the effects of cross sectional shape, molecular orientation, annealing and fibre type on the friction of polypropylene and acrylic yarns. Friction was dependent on shape as demonstrated in Figure 1.7.

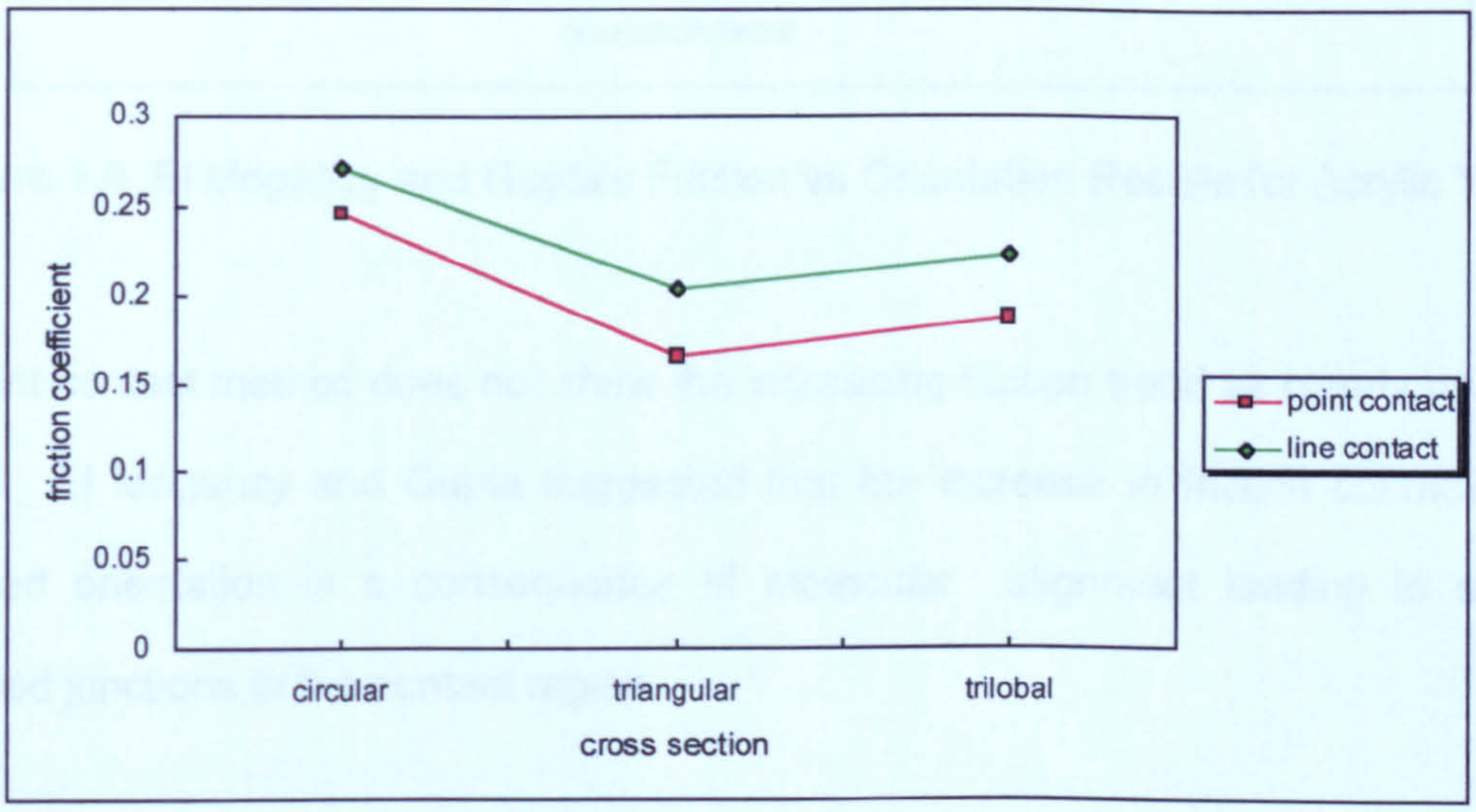


Figure 1.7 The Effect of Cross Section Shape on Acrylic Yarn Friction

(after El Mogahzy and Gupta, 1993)

Friction was higher for circular fibres than for triangular and trilobal ones. This is probably due to a greater contact area in the case of the circular cross section. El Mogahzy and Gupta also found that friction is higher for annealed than non-annealed structures. In addition, they found that friction increases with molecular orientation. This is demonstrated in Figure 1.8.

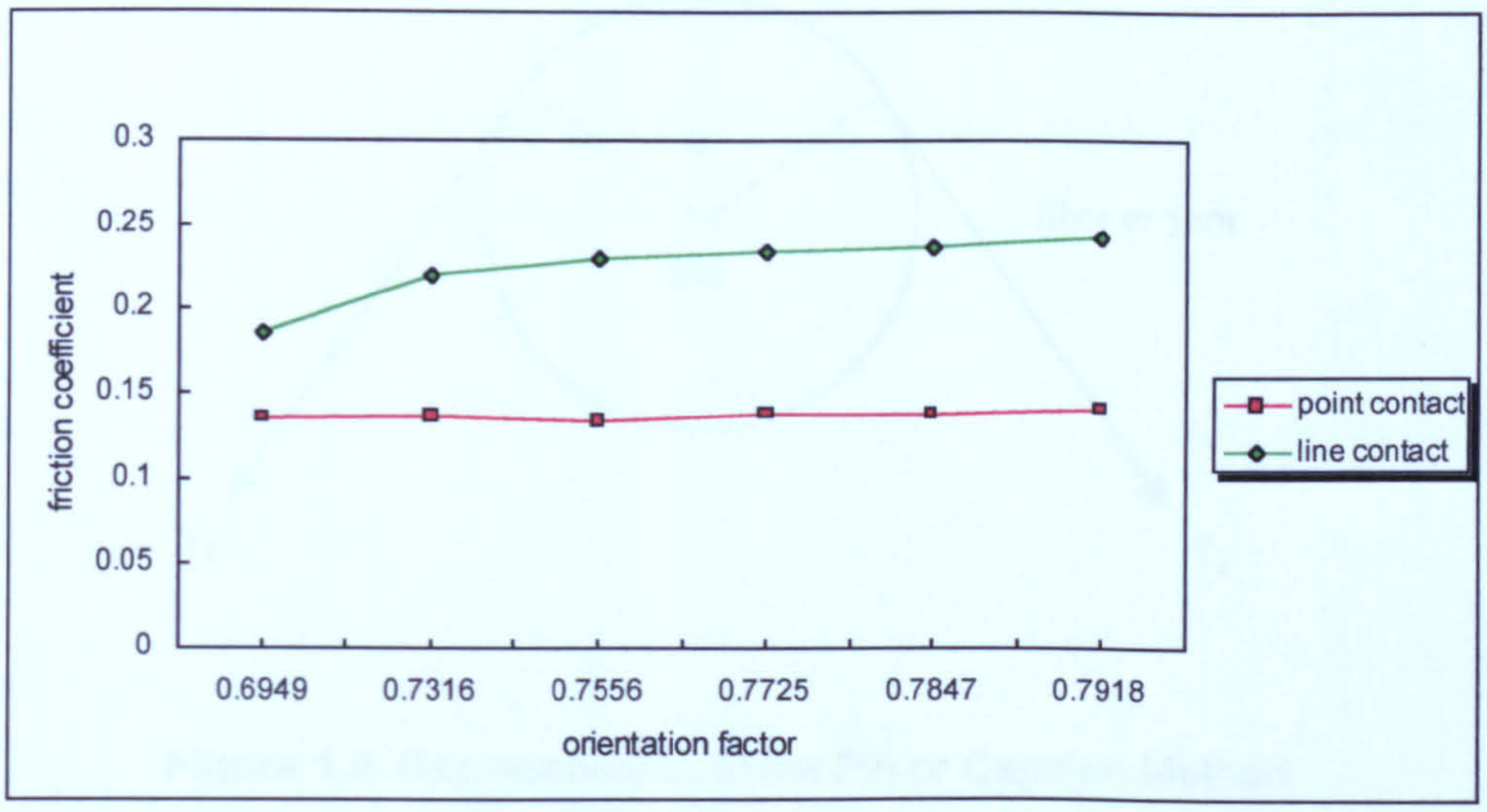


Figure 1.8 El Mogahzy and Gupta's Friction vs Orientation Results for Acrylic Yarns

The point contact method does not show the increasing friction trend as clearly as the line method. El Mogahzy and Gupta suggested that the increase in friction coefficient with increased orientation is a consequence of molecular alignment leading to stronger, reinforced junctions in the contact region.

1.3.7 Measurement of Friction

A number of methods are described in the literature to measure fibre friction. These include the rotating pin method (Buckle and Pollitt 1948, Röder 1953), the twist method (Lindberg and Gralen 1948), inclined plane and slider (Kalyanaraman and Praksam 1987) and pulling fibre assemblies apart (Lord 1955, El Mogahzy and Broughton 1993). The pin or capstan method was selected for the present project as the most suitable for measuring static and dynamic friction on finished fibre tow. The principle of operation is shown in Figure 1.9.

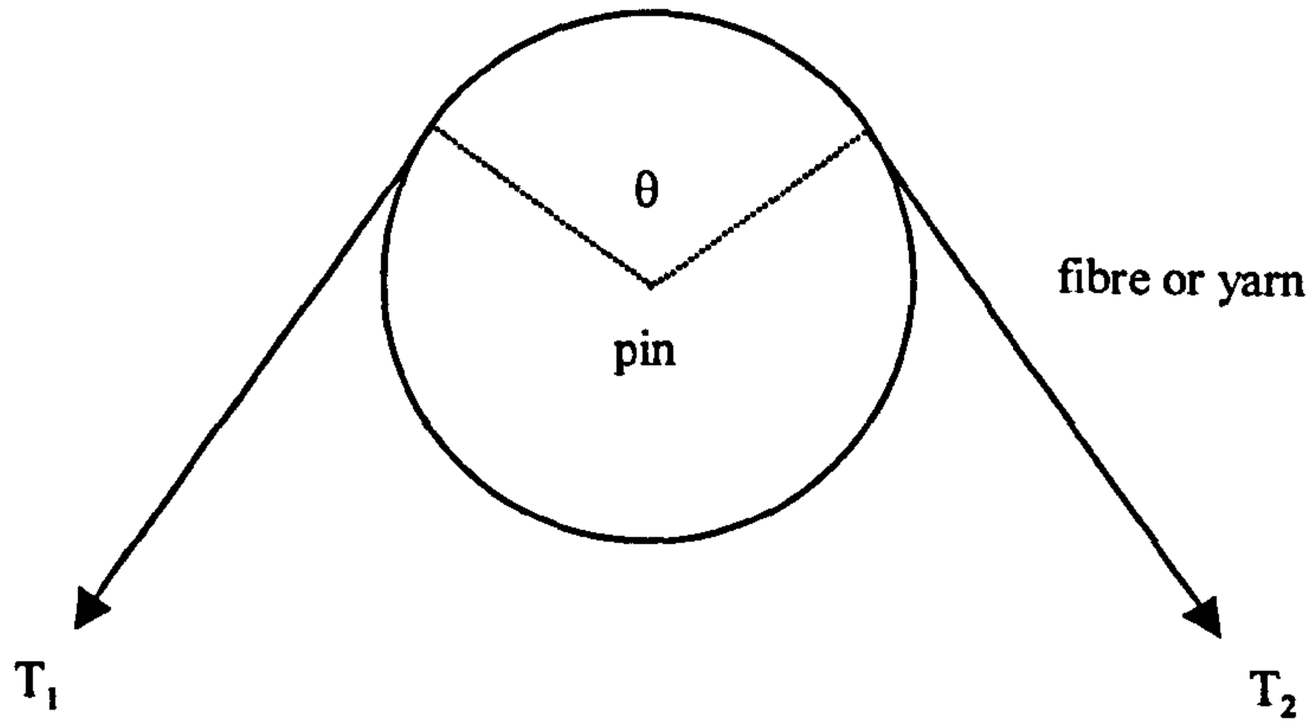


Figure 1.9 Representation of the Pin or Capstan Method

Simple analysis of results relies on the capstan equation

$$T_2/T_1 = e^{\mu\theta}$$

Where T_1 and T_2 are the initial and final fibre/yarn tensions, μ is the friction coefficient and θ is the wrap angle over the pin in radians.

Various feed, wind up and tension measurement arrangements have been described by workers using this method (Buckle and Pollitt 1948, Röder 1953 & 1955, Fort Jr. and Olsen 1961, Henshaw 1961, Olsen 1969, Robins, Rennell and Arnell 1988). The main elements of the measurements, however, remain the same, i.e. fibre or yarn is pulled over a stationary pin, or stationary fibre or yarn is wrapped around a rotating pin.

Fibre/metal or fibre/ceramic friction is measured by using a pin made from metal or ceramic material. To measure fibre/fibre friction the surface of the pin is covered with well adhered, aligned fibres as described by Robins *et al.* (1988).

Interpretation of the results can be complex. Rubenstein (1958a) derived a more detailed expression of the form

$$T_2^{1-n} - T_1^{1-n} = K(1-n)\rho_c^{1-n}\theta$$

where ρ_c is the radius of the pin, θ is the wrap angle and K and n are constants which depend on the fibre type. Values of n and K were given for viscose and cotton (amongst other materials). At a speed of 32.5 cm/s, a wrap angle of 180° and at 65.5 to 65.7°C, viscose and cotton yarns had values of n of 0.90 and 0.94 and K of 0.34 and 0.31 respectively. The friction surface was smooth glass.

When n » 1

$$T_2/T_1 = \exp\{K\theta(\rho/T_1)^{1-n}\}.$$

Further, if n = 1

$$T_2/T_1 = \exp(K\theta).$$

This is of the same form as the capstan equation, where K is analogous to μ. The value of n indicates the plasticity of the fibre or yarn. For fully plastic materials e.g. soft metals n=1.

Rubenstein made some general observations. When the yarn speed increased, K increased and n decreased. Lubricants did not affect n but reduced K.

Rubenstein (1963) also considered friction in the presence of a viscous lubricant on the fibre or yarn surface. He proposed that

$$T_2/T_1 = \{F_0\rho(e^{\mu\theta}-1)/\mu T_1\} + e^{\mu\theta}$$

where F_0 is the frictional resistance due to viscous drag.

Howell (1953) considered the general case of the friction of a string around a cylinder. He derived the expression

$$T/T_0 = [1 + (1 - n)a(\rho/T_0)^{1-n}\theta]^{1/1-n}$$

where T_0 and T are initial and final tensions, ρ is the cylinder radius, θ is the wrap angle and n and *a* are the friction constants. He simplified this to

$$T/T_0 = \exp(a[\rho/T_0]^{1-n}\theta).$$

The friction coefficient μ can now be considered as

$$\mu = a(\rho/T_0)^{1-n}.$$

Howell defined the extremes of n as 0.67 and 1.0 for perfectly elastic and plastic surfaces respectively. The above expression suggests that the coefficient of friction is greater for larger cylinders than for small ones, however, provided the cylinder radius is kept constant, useful comparisons of various lubrication treatments can still be made.

Merkel (1963) used Howell's approach on cotton using the modified equation

$$(T_2/T_1)^{1-n} = 1 + C/T_1^{1-n}$$

where C is a constant. He found n to be 0.83 and 0.80 at 3.6 cm min^{-1} and 200 cm min^{-1} respectively, suggesting that cotton is more elastic at higher speeds.

Howell (1954) also observed that when a glass cylinder was clean, static and kinetic friction coefficients against nylon fibre were the same. When the glass was contaminated the kinetic coefficient was smaller than the static coefficient.

An article from the Shirley Institute Bulletin (Anon, 1950) suggests that when making friction measurements by the pin method, the speed, fibre or yarn tension, relative humidity (%r.h.) and temperature should be specified, although temperature appears to have a much smaller effect than %r.h. When measuring yarn friction the twist factor is important. Increased twist reduces flattening, hence reducing contact area, so the contact pressure increases and the friction is reduced.

Rubenstein (1958b) suggested that decreasing ρ/T_1, increasing temperature, or decreasing the speed had the effect of reducing α, which is analogous to a friction coefficient in the equation

$$T_2/T_1=e^{\alpha\theta}.$$

He calculated that errors introduced when using the pin method can be minimized if $\alpha\theta\leq0.5$, where θ is the wrap angle.

Makinson (1970) used the pin method to measure the friction of wool fibres. She took the additional step of immersing the rod (pin) in water, hence wet friction could be measured successfully.

Finally, Grosberg and Plate (1971) considered bending-hysteresis losses to be important in capstan (pin method) friction measurements. They suggested that an extra force is required to bend and restore fibres or yarns as they pass around a capstan then become straightened. This can account for up to 25% of the measured force at small wrap angles. Hence higher friction than the true value might be measured when bending hysteresis is neglected. Fortunately this extra force reduces dramatically as the pin radius is increased above 1cm.

The papers identified here suggest that the pin method is suitable for measuring friction in the speed range 0.01 to 6.0 ms^{-1}. The load and lubricant viscosity should be taken into account, but over this speed range boundary, semi-boundary and hydrodynamic friction

can be covered. Whether simple or complex analysis is undertaken depends on the type of information required.

1.4 CONCLUSIONS FROM THE LITERATURE

From the literature concerning fibre finishes and textile friction, several conclusions are drawn.

Finishes are essential processing aids which provide lubrication and reduce static accumulation in the conversion of fibres to yarns through carding, drafting and spinning. There are a number of ways of applying finish either in neat form or in an emulsion. Common methods employed are deposition from a bath, via lick or kiss rolls, spraying or direct application from a metered pump. The most convenient system depends on whether the fibres are in staple or tow form.

The analysis of finishes on fibres usually relies on the addition of tracers to the finish in order to determine the surface distribution, or extraction of the deposit from the fibres, which requires further analysis to reveal the chemical composition. This gives rise to the need for a method to observe finishes on fibres directly, without the need for tracers or extraction.

Wet lubricants are used commonly in the textile, food, plastic and other industries. In the literature, information is sparse on the understanding of the way in which wet lubricants work.

Textiles do not behave according to the usual descriptions of friction (Amontons' law), associated with plastic materials such as sliding metals. Textiles have a degree of elastic behaviour in sliding and there have been many attempts to describe this. Textile friction depends on many factors such as load and hence pressure and contact area, speed, finish type, viscosity and amount on fibre, roughness, humidity and moisture content, fibre type and physical form, temperature, wetting behaviour, yarn and fabric construction, the material of the contact surface and so on.

There are many ways of measuring textile friction. In the present work, the pin or 'capstan' method was selected as most suitable.

CHAPTER 2

DEPOSITION AND CHARACTERISATION OF A FIBRE FINISH

2.1 EXPERIMENTS DESIGNED TO INVESTIGATE THE EFFECTS OF DEPOSITION CONDITIONS ON FINISH COMPOSITION AND DISTRIBUTION

The performance of finishes applied to facilitate the conversion of fibres into yarns through carding, drafting and spinning depends on their friction and antistatic characteristics, as reported by Röder (1953 & 1955), Billica (1977), Graham *et al* (1977), Szklarek (1985), Papendick (1986), Haigh and Harrowfield (1990), Broughton Jr and El Mogahzy (1993) and Becker (1993). These properties are related to the surface composition of the applied finish as shown by Schick (1973b). The deposited surface layer may differ markedly from the bulk composition of the application bath as reported by Bräuer *et al* (1985), Hough and Rendall (1983) and Hellsten *et al* (1989). The cost and performance optimisation of fibre finishes should therefore be based on a knowledge of the surface composition and distribution of the final finish delivered to the fibre. Until recently such detailed analytical information has been difficult to obtain, but the increasing availability of secondary ion mass spectrometry (SIMS) now provides for relatively straightforward analysis.

Reed (1989) discussed the use of SIMS to analyse the surface composition of polymer blends and Batts and Paul (1994) used the technique to investigate the coverage of a gelatin surface by a fluorosurfactant. More recently Shao *et al* (1997) have applied SIMS to probe the nature of surface lipids on wool fibres.

In the present work the principal components of a commercial finishing system were used to produce SIMS calibration spectra. These were then used to analyse the surface composition of the finish when applied to viscose fibres from emulsions of varying composition, and under a range of different application regimes.

2.1.1 Experimental

2.1.1.1 Materials

The antistatic agent Nopcostat 092 (092) and the lubricant PEG 200 dilaurate (P2DL) were used as received from Henkel Performance Chemicals, Leeds, UK. These are proprietary products used widely in fibre finishes. Their purities and exact structures are not disclosed, they are however described as a "cationic fatty derivative" and a "polyglycol diester" on their respective material safety data sheets.

Fibres for the deposition experiments were unfinished viscose tow, 1.7 dtex, from Courtaulds European Fibres, Grimsby, UK. These were extracted in methanol (6 hours) and then in hexane (6 hours) before depositing the finishes.

2.1.1.2 Methods

Application of Neat Surfactants onto Paper and Fibre Substrates

For calibration purposes, neat 092 and P2DL were applied (a) individually and (b) in mixtures containing from 10/90, to 90/10, 092/P2DL in 10% increments. Liquid mixtures (1g) were prepared by weighing accurately the appropriate amount of each component into glass tubes. The tubes were closed and warmed in an oven at 40°C such that both surfactants were liquid and easily mixed. All surfactant mixtures were prepared in duplicate.

Calibration spectra were generated from films of the neat surfactants and their mixtures, spread onto small squares (5mm) of Xerox photocopy paper. This substrate was flat and provided a convenient surface to analyse, whilst having similar surface chemistry to cellulose fibres. Although a non-absorbent substrate, such as a clean silver disc, is often preferred, this was considered to have the disadvantage of being too dissimilar from the viscose fibres used in the present work.

Also for calibration purposes, surfactants were applied to the viscose fibres by dipping fibre bundles (1000 fibres approx.) trimmed to about 1cm length, into the well stirred neat surfactants and then padding gently with paper towels to remove excess surfactant.

Deposition of Surfactant Emulsions onto Viscose Fibres

Surfactant emulsions were prepared by weighing appropriate quantities of 092 and P2DL to give the required component ratios, and diluting with distilled water to give the required concentrations (Table 2.1). The diluted surfactants were agitated vigorously to form emulsions which were stable over the deposition times employed. The set of experiments is based on a half 2^4 factorial (Cochran and Cox, 1957). Three replicates (experiments 9,10 and 11) were added with variables set at their mid values to give a measure of variability.

Table 2.1 Conditions Used to Deposit Surfactant Emulsions on Viscose Fibres

Experiment	%092:P2DL in emulsion	Emulsion conc. g/l	Deposition temp. °C	Deposition time s
1	1:99	1	21	1
2	20:80	50	21	1
3	20:80	1	80	1
4	20:80	1	21	60
5	1:99	50	80	1
6	1:99	50	21	60
7	1:99	1	80	60
8	20:80	50	80	60
9	10:90	25	50	30
10	10:90	25	50	30
11	10:90	25	50	30

Finish was applied by immersing fibres (17g batches) for the required lengths of time in the emulsions maintained at the required temperatures (Table 2.1). The fibres were drained in a fine mesh sieve and squeezed in a laboratory mangle to remove excess emulsion. The fibres were then spread out on paper towels and oven dried for 30 minutes at 110°C. This application regime was chosen to correspond approximately to a typical production finishing procedure for viscose tow.

Secondary Ion Mass Spectrometry

SIMS was carried out using a Kratos Prism time-of-flight spectrometer in the static mode, so that sample damage was at a minimum, and characteristic species were ejected from only the outermost monolayer of the sample surface. Specimens mounted on a sample stub and held under a high vacuum (10^{-7} Torr approx.) were bombarded with a focused beam of mono-isotopic gallium ions. These primary ions were accelerated through 25kV and pulsed (100ns cycle). Each specimen received 1

million pulses over an area of 333μm x 333μm such that the total dose was $<10^{12}$ ions cm^{-2}. Secondary ions originating from the sample surface were expelled, extracted and detected in the mass spectrometer. Once characteristic peaks for 092 and P2DL had been identified, mass windows of ±5 amu were set for integration of the areas under these peaks.

In the calibration experiments five different regions (each 333 μm square) of each paper and fibre sample were examined in order to obtain information on the variation of surface composition across the samples. For each region the mean 092 and P2DL peak areas (i_{092} and i_{P2DL}) were determined and the 092 intensity ratio, i.e. $i_{092}/(i_{092}+i_{P2DL})$, was calculated. The procedure was repeated for a duplicate set of neat surfactants and mixtures applied to the paper substrate only.

SIMS spectra were also obtained from fifteen regions of each of the viscose samples, which had been finished with the surfactant emulsions.

X-Ray Photoelectron Spectroscopy (XPS)

XPS measurements were made on the 50/50, P2DL/092 calibration sample on the paper substrate using a Kratos Axis instrument operating with a Mg Kα radiation source. Spectra were recorded at take-off angles (with respect to the normal from the sample surface) of 0° and 60°.

Solvent Extraction and Infrared Analysis

Following removal of the specimens required for SIMS analysis from the finished 17g samples, the remaining fibres were soxhlet extracted in methanol for 3 hours and the

extract weighed after evaporation of the solvent. This allowed calculation of the % surfactant on fibre, based on the weight of the fibres before extraction.

The ratio of 092 to P2DL in the bulk finish was determined by analysis of the extracts via infrared spectroscopy (IR). Spectra were obtained using a Nicolet 740 FTIR spectrometer, equipped with an MCT detector and a single reflection, diamond attenuated total reflection (ATR) accessory.

Nopcostat 092 and P2DL have characteristic IR absorbance bands at 1018 cm^{-1} and 1109 cm^{-1} respectively. IR spectra of the two materials are shown in Figure 2.1a and 2.1b.

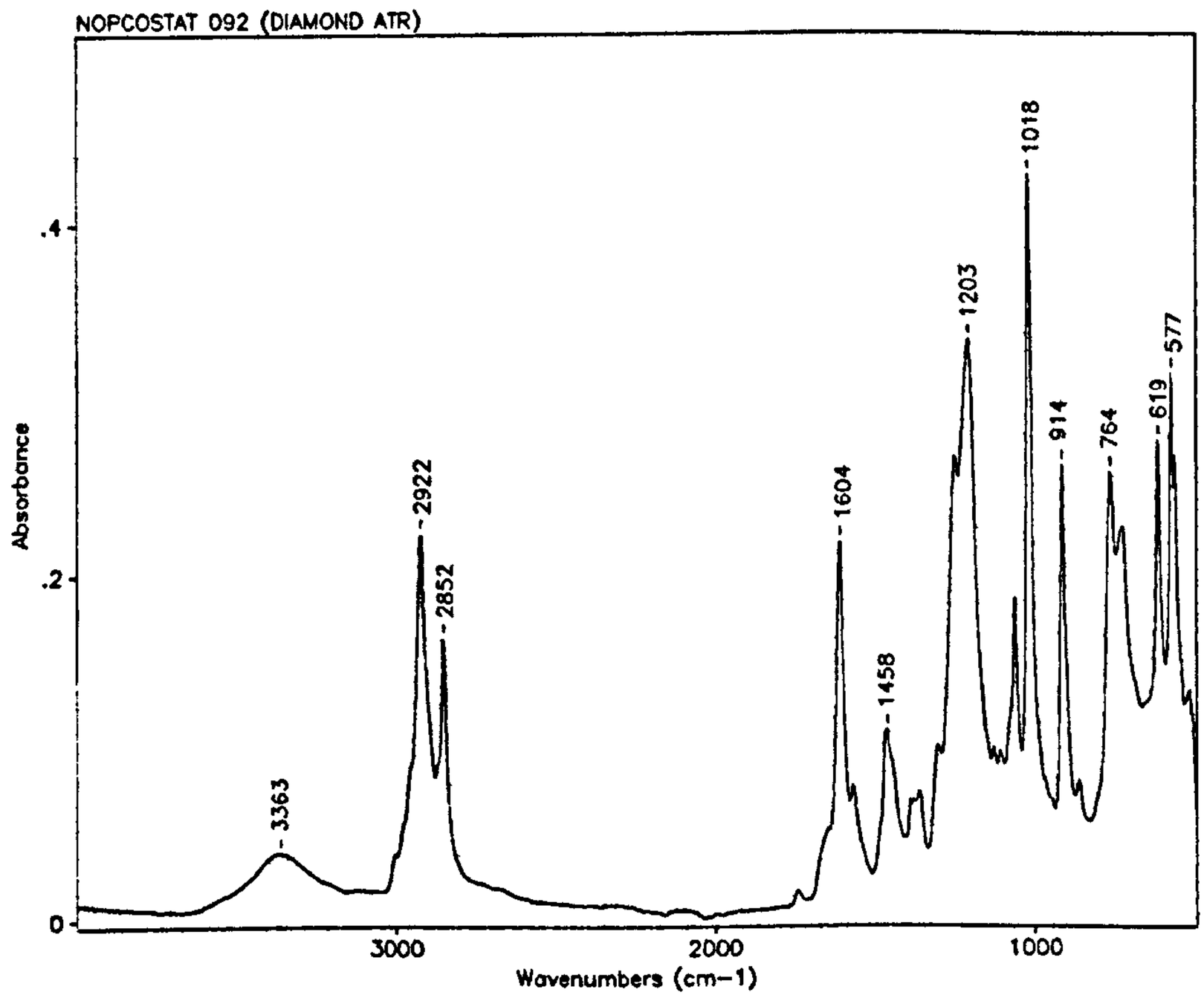


Figure 2.1a IR Spectrum of Nopcostat 092

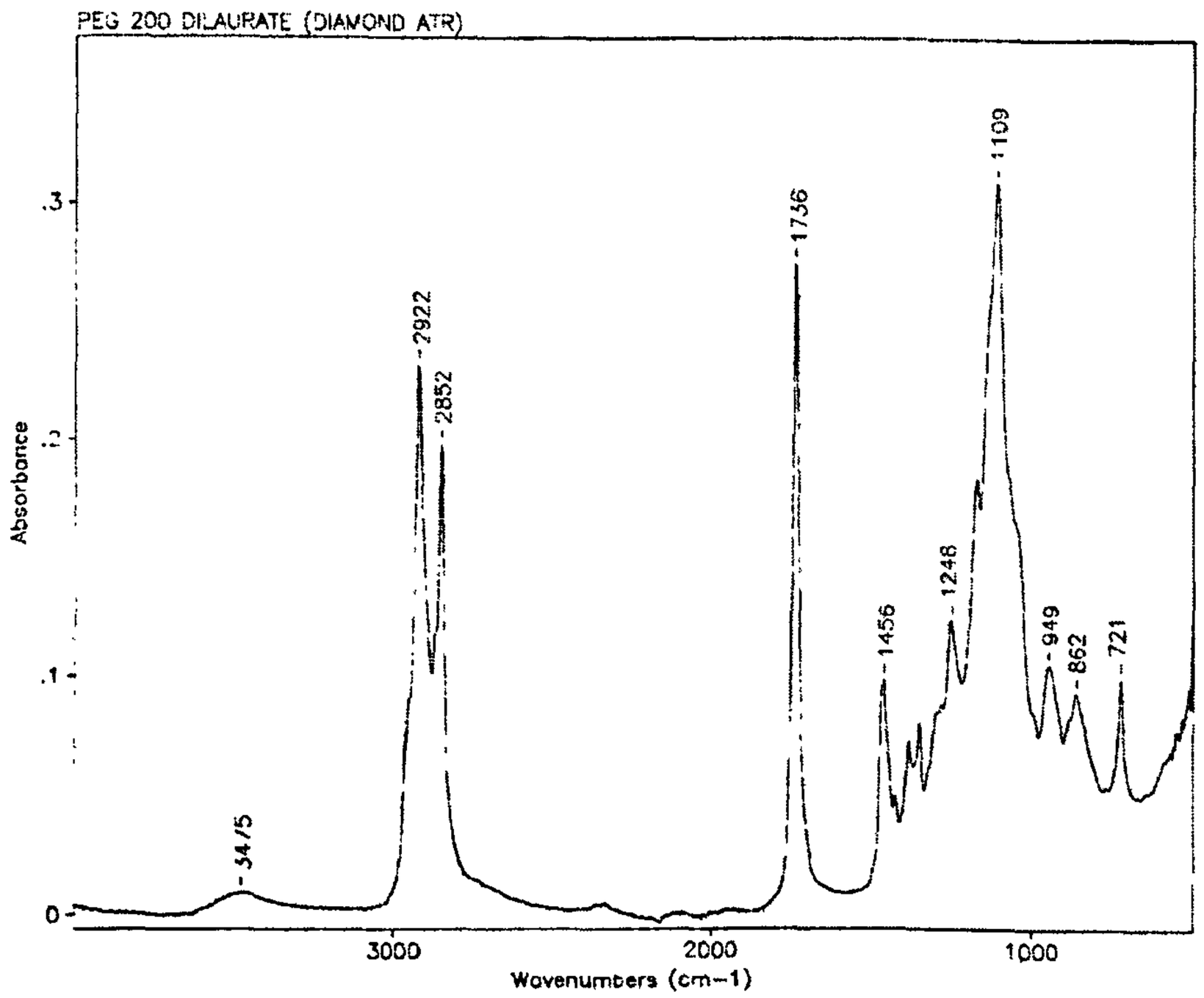


Figure 2.1b IR Spectrum of PEG 200 Dilaurate

Changes in the ratio of these bands were related to composition changes using a partial least squares model (PLS+/IQ in GRAMS/32). The same neat P2DL and 092 samples and mixtures as used for SIMS were analysed in an IR calibration. Compositions of the fibre finish extracts were calculated from their IR spectra using the partial least squares model.

2.1.2 Results and Discussion

2.1.2.1 Calibration for SIMS

Figure 2.2 shows the positive secondary ion mass spectra obtained from (a) the Xerox photocopy paper and (b) the extracted viscose fibres, without the application of fibre finish surfactants. The characteristic peak for both cellulose substrates occurred at 149 amu.

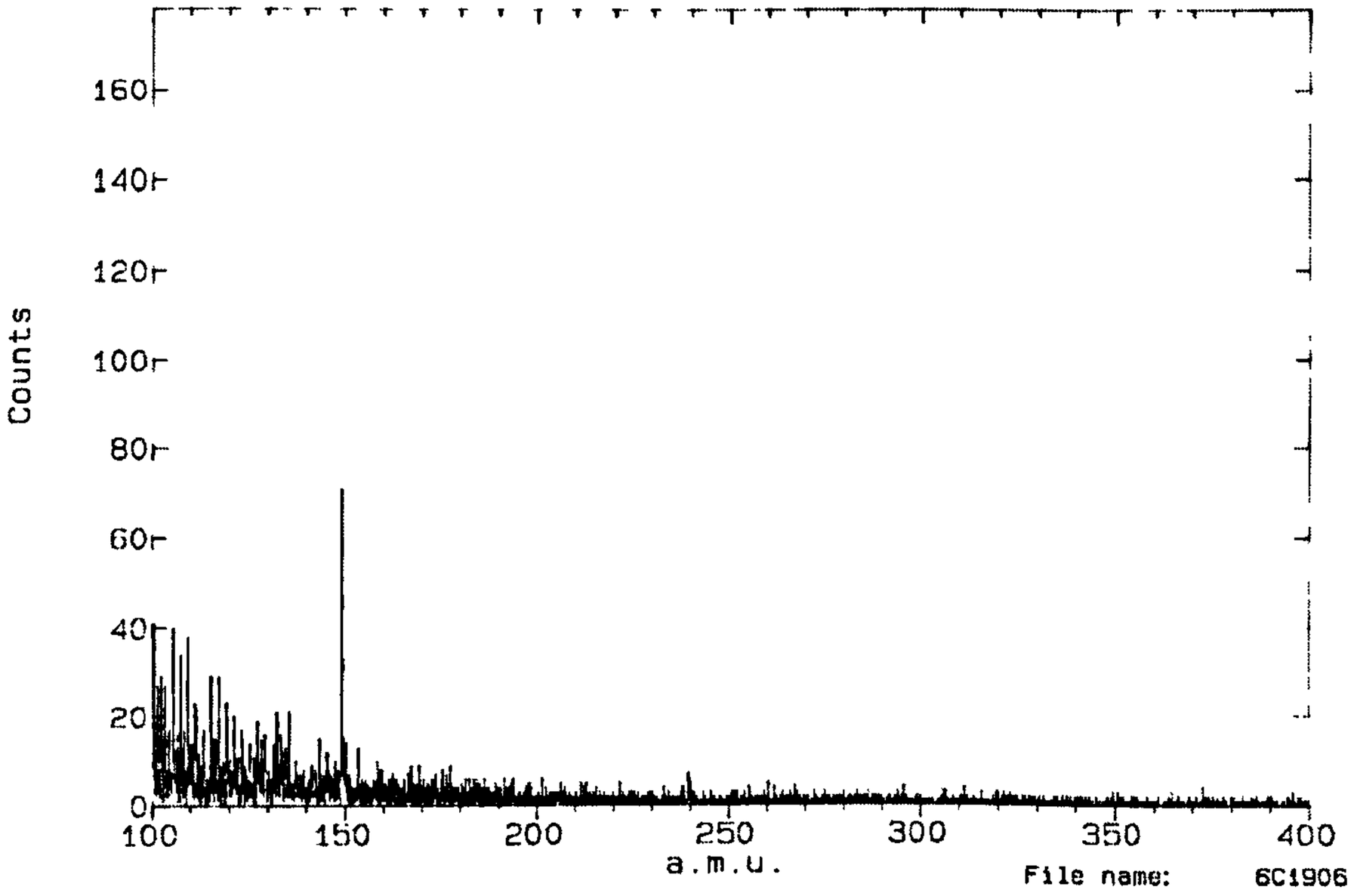


Figure 2.2a Positive SIMS Spectrum of Xerox Paper

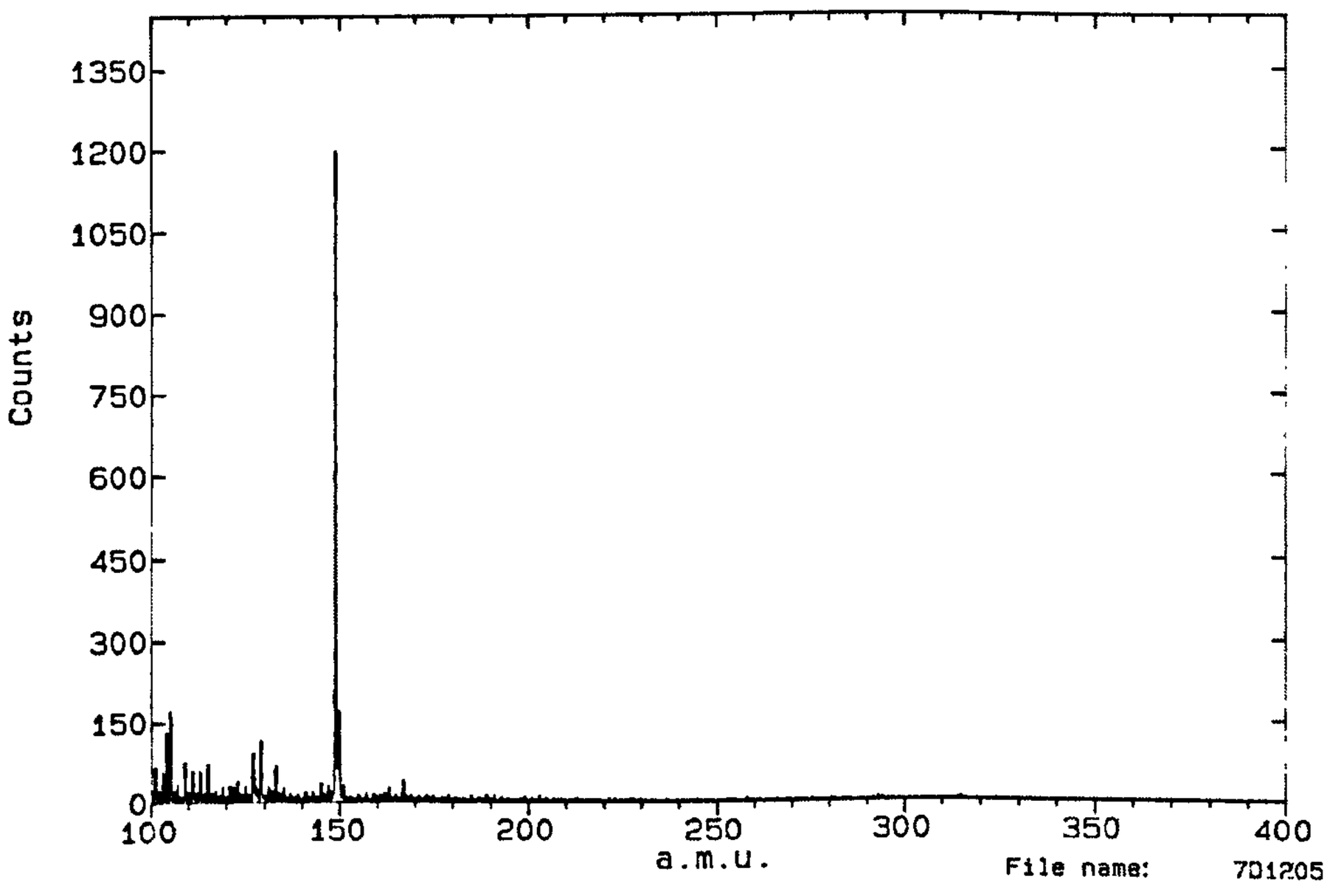


Figure 2.2b Positive SIMS Spectrum of Extracted Viscose Fibres

The positive secondary ion mass spectra obtained for (a) P2DL and (b) 092 when applied neat to the paper substrate are given in Figure 2.3. The characteristic substrate peak at 149 amu is absent, indicating complete coverage by the surfactants.

The most distinct peaks for P2DL and 092 are at 227 amu and 379 amu respectively. Each of these components has its own "fingerprint" spectrum arising from secondary ions which correspond to molecular weight distributions and fragmentation patterns.

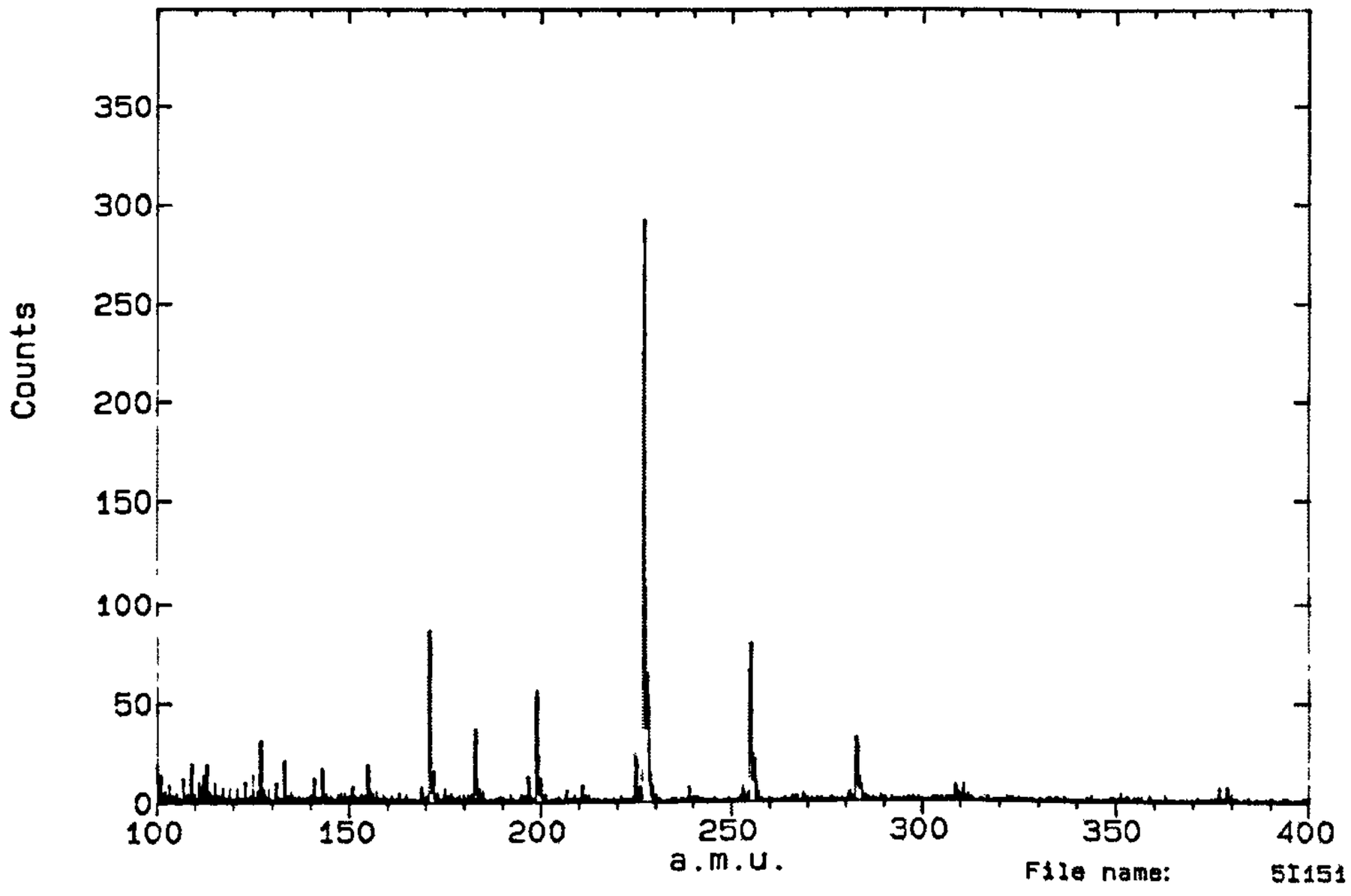


Figure 2.3a Positive SIMS Spectrum of P2DL on Xerox Paper

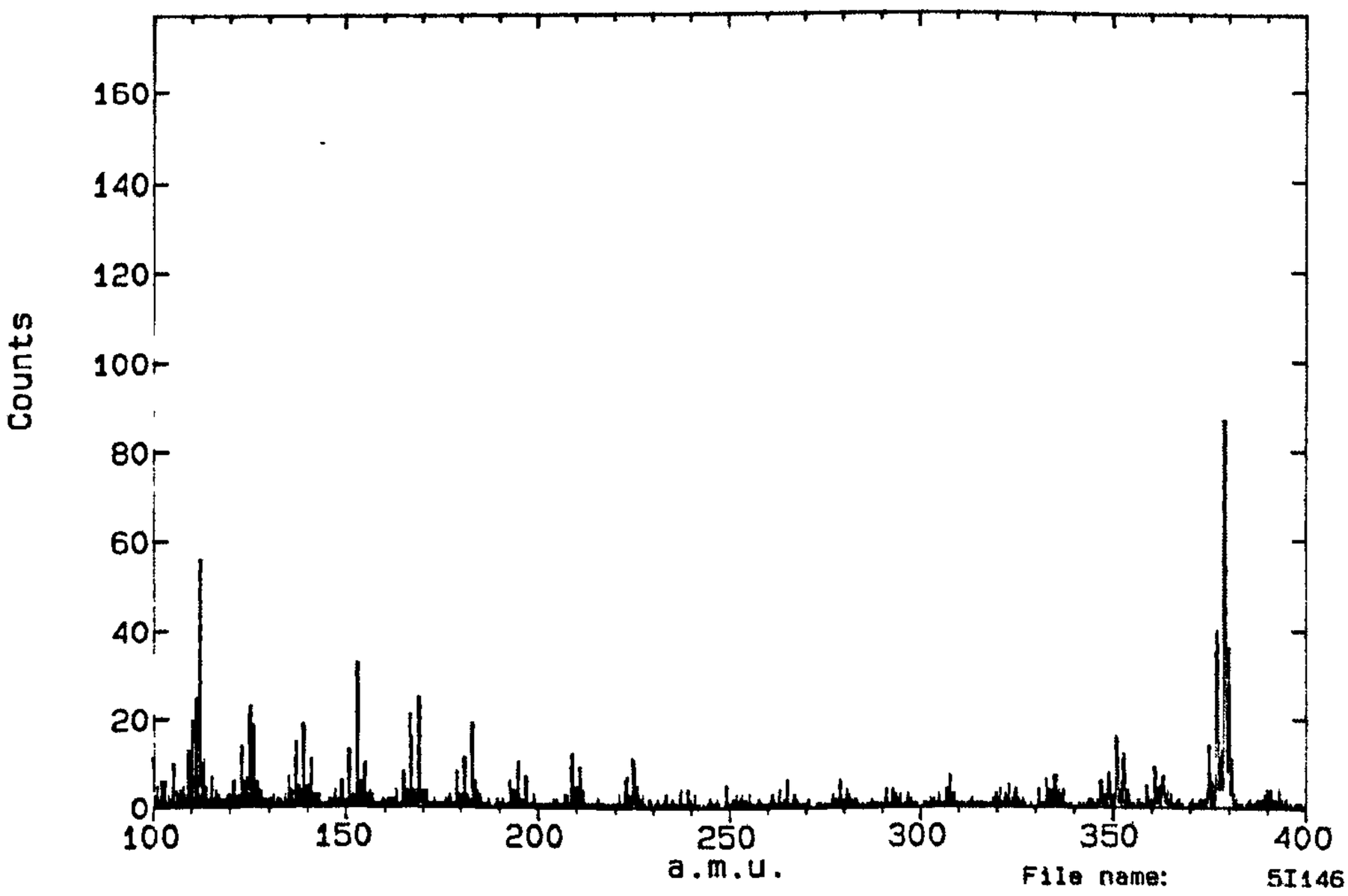


Figure 2.3b Positive SIMS Spectrum of 092 on Xerox Paper

Figure 2.4 shows the spectra obtained for a 50/50, P2DL/092 neat surfactant mixture applied (a) to paper and (b) to viscose fibres.

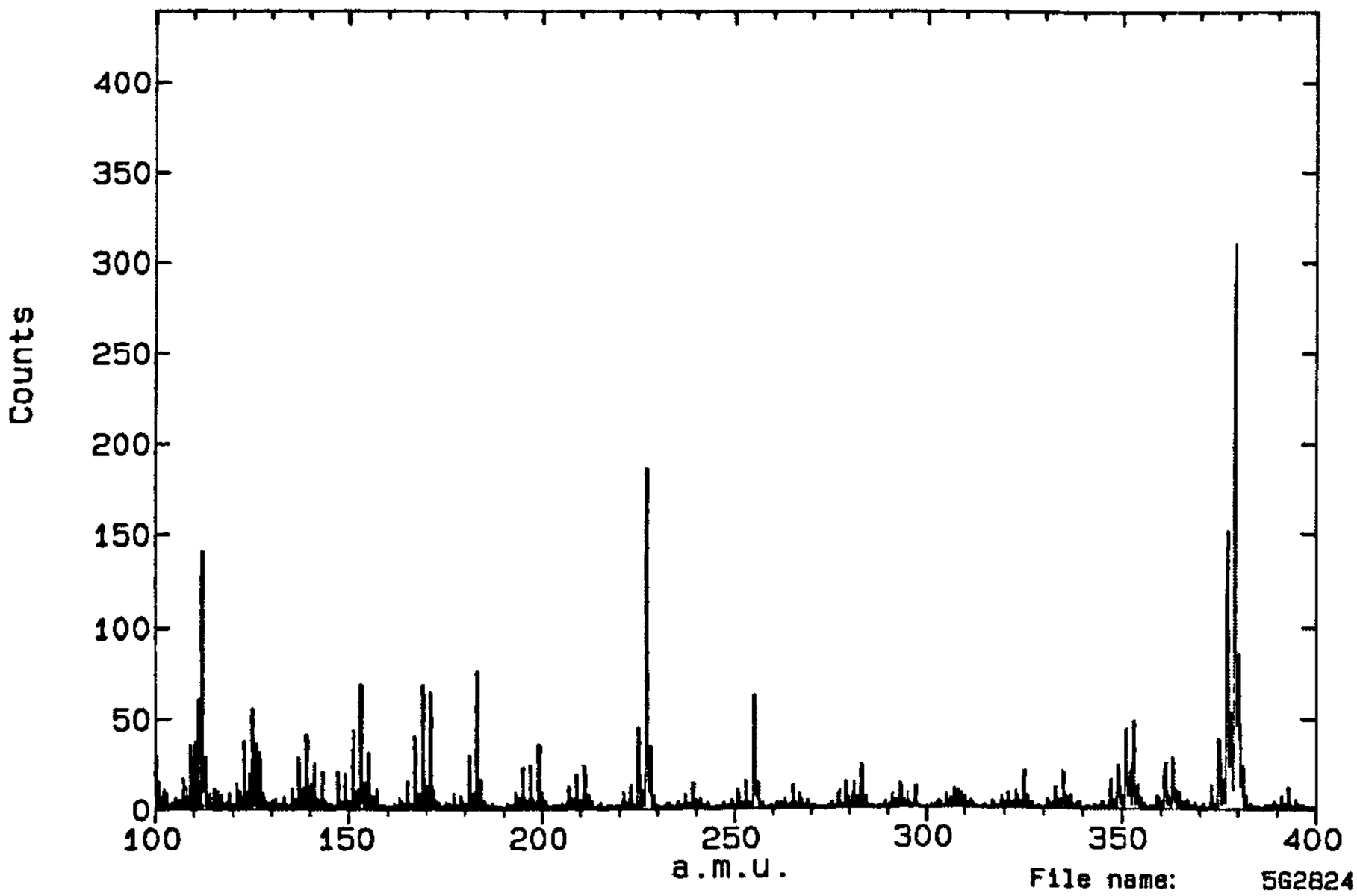


Figure 2.4a SIMS Spectrum of P2DL/092 (50:50) on Xerox Paper

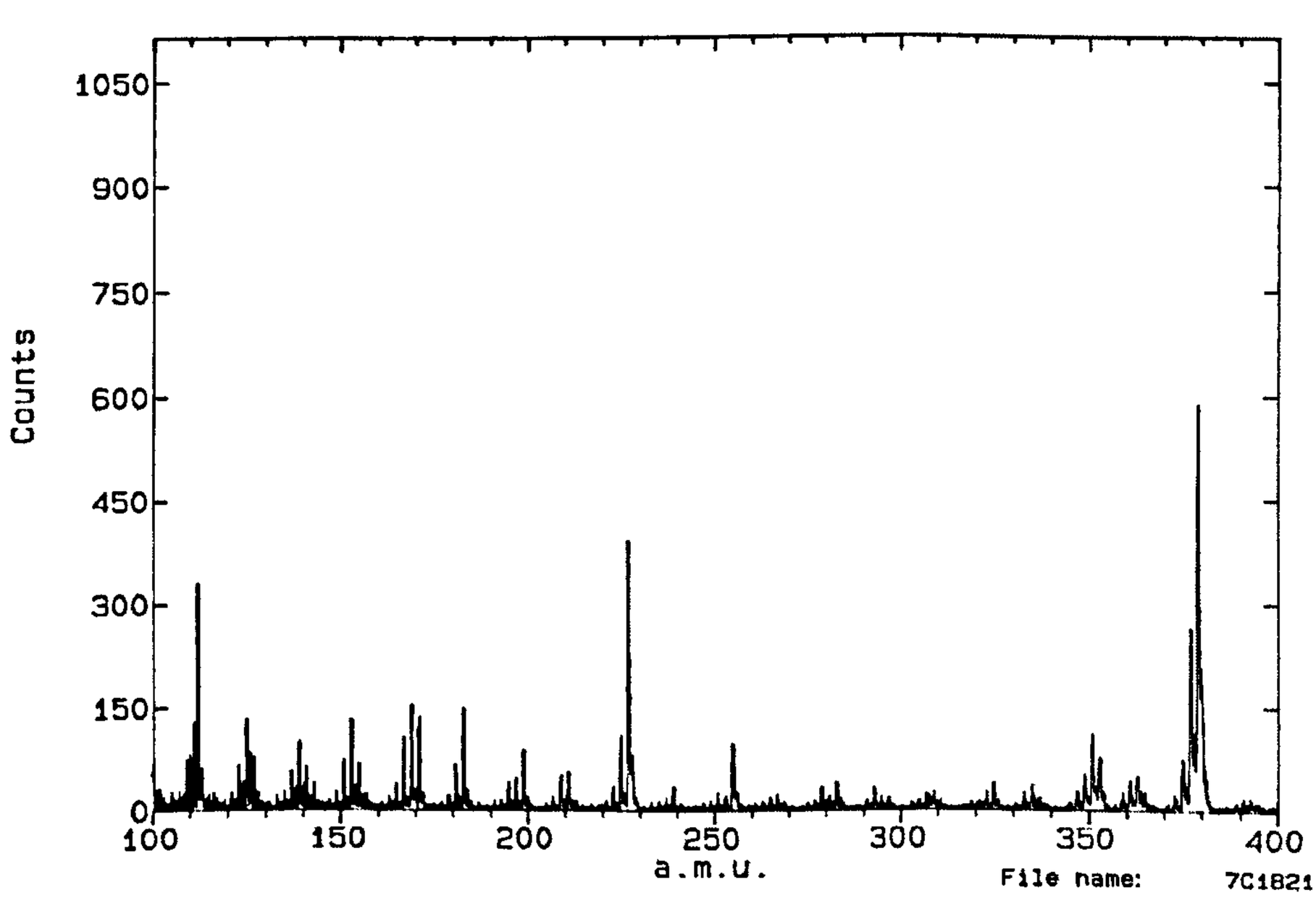


Figure 2.4b SIMS Spectrum of P2DL/092 (50:50) on Viscose Fibres

The 092 intensity ratio, $i_{092}/(i_{092}+i_{P2DL})$, was calculated from each of the five spectra obtained from the duplicate sets of calibration samples applied to the paper substrate.

A model was fitted to the data,

$$092 \text{ ratio} = 0.086 + 0.085\ (\%092)^{1/2}.$$

Here, %092 refers to the %092 at the surface compared to P2DL. On the calibration samples it is assumed that %092 at the surface is the same as the bulk composition. This is reasonable since the components were well mixed and spread evenly on the paper substrate. This assumption is supported by the XPS analysis of the 50/50, P2DL/092 mixture on paper (Table 2.2).

Table 2.2 Atomic Composition of 50/50 P2DL/092 Mixture Determined by XPS

Element	0° TOA	60° TOA
C	79.9	80.7
O	15.6	14.4
N	2.6	2.8
S	1.5	1.3
Si	0.5	0.8

Since the atomic composition remained essentially constant at the two take off angles, which represent different depths from the sample surface, the mixture is believed to be homogeneous. The appearance of silicon is attributed to contamination.

The 99% confidence intervals were calculated from the combined standard deviation (CSD) of all paper substrate calibration data (CSD value = 0.030). Data points from both sets of calibration specimens are shown in Figure 2.5 together with the upper and

lower 99% confidence intervals. There was a 97% fit between the model and the data (R^2=0.97).

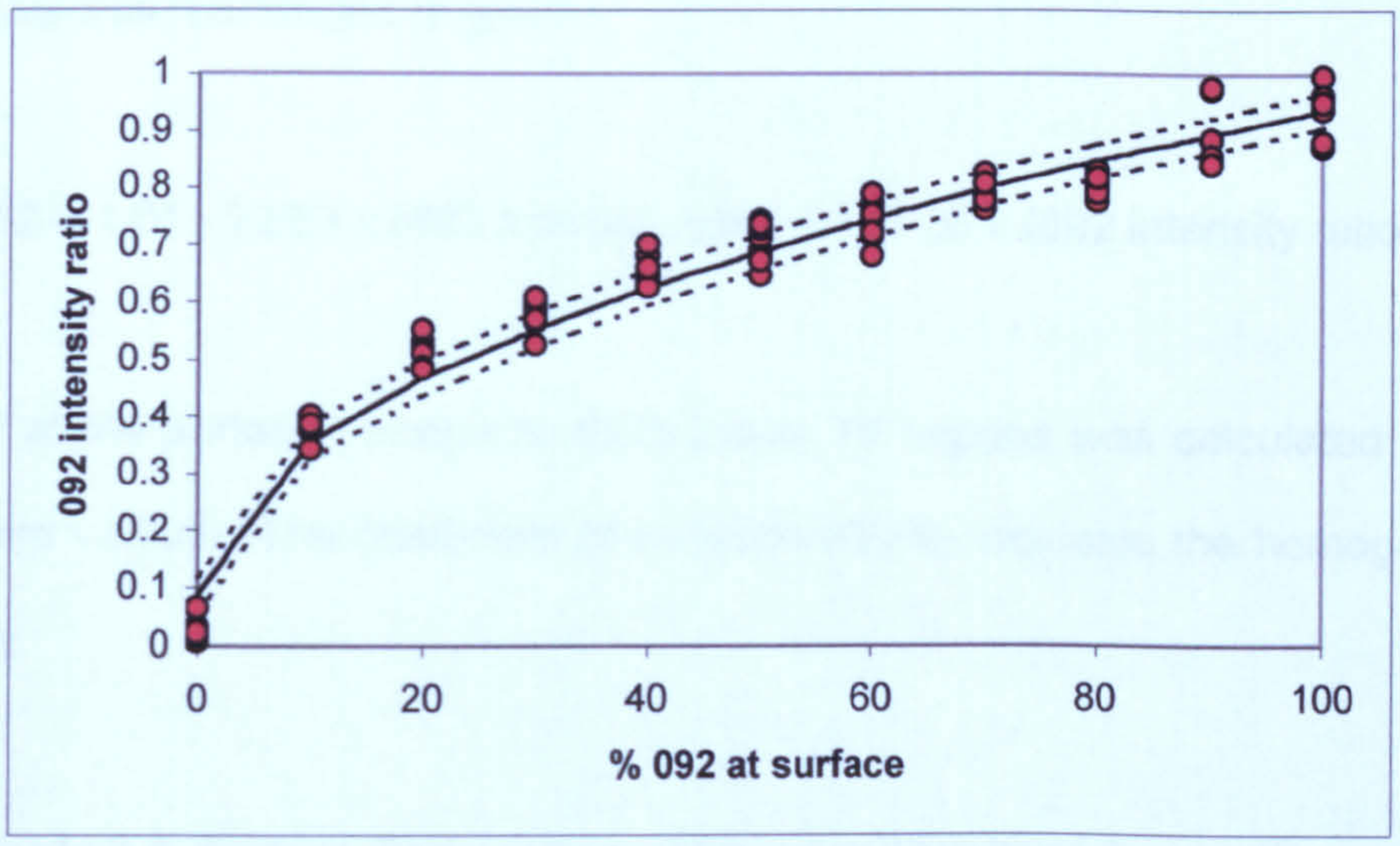


Figure 2.5 SIMS Calibration From Neat Components Applied to Paper Substrate

● = data ——— = model ····· = 99% confidence interval

SIMS 092 ratios from neat 092 and P2DL mixtures, applied to viscose tow, were compared with the model derived using the paper substrate. Reasonable agreement (92% fit) was obtained and it is therefore concluded that calibrations based on neat surfactants applied to a paper substrate (for convenience and homogeneity) are valid for analysis of the surfactants applied to viscose tow.

The curvature in the calibration (Figure 2.5) indicates that the yield of the 092 ions is not independent of the matrix, otherwise the calibration plot would have been a straight line. Reed (1989) comments on this effect in an EMA-HEMA copolymer system, where a plot of the relative ion intensity versus composition was also curved.

2.1.2.2 Analysis of Finishes Applied From Emulsion

The 092 and P2DL peak areas obtained by SIMS from the finishes applied from emulsions were converted to %092 at the surface via the model described in section 2.1.2.1. This was rearranged to give:

$$\%092 = 1.01 - 23.63 \times (092 \text{ intensity ratio}) + 137.86 \times (092 \text{ intensity ratio})^2.$$

The %092 at the surface (relative to P2DL) over 15 regions was calculated for each finished fibre variant. The coefficient of variation (CV%) indicates the homogeneity of the surface.

Table 2.3 Surface Composition of Emulsion Finished Viscose Fibres

Experiment	%092 at surface	Standard deviation	CV%
1	0.5	0.3	60
2	4.9	11.1	228
3	1.1	2.8	249
4	1.8	2.7	146
5	2.6	2.7	104
6	1.1	1.4	134
7	0.3	0.2	87
8	20.3	15.1	74
9	4.0	7.2	178
10	5.4	8.2	151
11	3.0	5.0	169

The replicates with variables at their mid values (experiments 9, 10 and 11) showed reasonable agreement. Some experiments had standard deviations greater than the %092 (i.e. CV%>100%). This suggested that some regions did not have any 092 at

the surface and this was confirmed by their SIMS spectra and would correspond to a poor distribution of 092. Complete coverage by P2DL or 092 was achieved on all regions as the 149 amu cellulose peak was not apparent in the spectra.

The % solvent extract from each variant (i.e. %finish on fibre) and the %092 in the extract (relative to P2DL) analysed by IR, are shown in Table 2.4. SIMS analysis of % 092 at the surface and %092 in the finish bath are included for comparison.

Table 2.4 Comparison of Bulk, Surface and Emulsion Finish Compositions

Experiment	%extract	%092 in extract	%092 at surface	%092 in emulsion
1	0.2	5	0.5	1
2	2.1	17	4.9	20
3	0.6	9	1.1	20
4	0.3	9	1.8	20
5	1.8	3	2.6	1
6	3.6	3	1.1	1
7	0.8	4	0.3	1
8	4.7	13	20.3	20
9	3.7	7	4.0	10
10	4.3	6	5.4	10
11	3.7	7	3.0	10

There is no significant correlation between %092 at the surface and the deposition variables shown in Table 2.1. This suggests that the amount of 092 relative to P2DL at the finished fibre surface was independent of the deposition conditions. There is a weak correlation (R=0.58) between the homogeneity of the surface, indicated by CV% (Table 2.3), and %092:P2DL in the emulsion, although it is not significant at the 5% level (Caulcutt, 1995) at which $R_{critical}$= 0.60.

The %092 in the finish extracted from the fibres shows a strong correlation with %092 in the emulsion (R=0.85). This is significant at the 1% level ($R_{critical}$= 0.77). Unsurprisingly, more 092 in the emulsion produced more 092 in the bulk extract.

The total %extract (092 and P2DL) showed some dependence on the emulsion concentration (R=0.67). The correlation is significant at the 5% level ($R_{critical}$=0.60).

The significant link between %092 in the emulsion and %092 in the finish extract has been demonstrated. Also the surface composition has been shown not to depend on the deposition conditions. There was only a weak correlation between the surface and bulk %092:P2DL (R=0.53). Hence, the surface composition was not the same as the finish deposited through out the fibre bulk. The surface composition bore no resemblance to the emulsion composition.

Mc Dermott et al (1993) have also shown that the composition of a mixed layer of non-ionic and cationic surfactants adsorbed onto a hydrophilic surface was quite different to the composition of the bulk solution. In this case, the deposited layer was close in composition to that predicted for mixed micelles. The P2DL and 092 used in this work are from commercial sources and incomplete information on their structures and purity makes prediction of the emulsion droplet composition impossible.

Drying conditions could affect the surface composition if components of differing volatility are lost in varying amounts. On this basis, it would be impossible to predict the distribution of finish components from knowledge of the emulsion make-up. Predicting friction and processing behaviour would also be unreliable. From this study it can be concluded that it is not feasible to control the surface composition of a deposited two component emulsion by changing the deposition conditions.

2.2 FRICTIONAL PROPERTIES OF FINISHED FIBRES AND THEIR CORRELATION WITH FINISH APPLICATION CONDITIONS

2.2.1 Experimental - Friction Measurements

The pin or capstan method (see section 1.3.7) was selected as the most convenient for measuring fibre/metal and fibre/fibre friction since the fibres were in the form of lengths of tow. The method is suitable for measuring both static and dynamic friction.

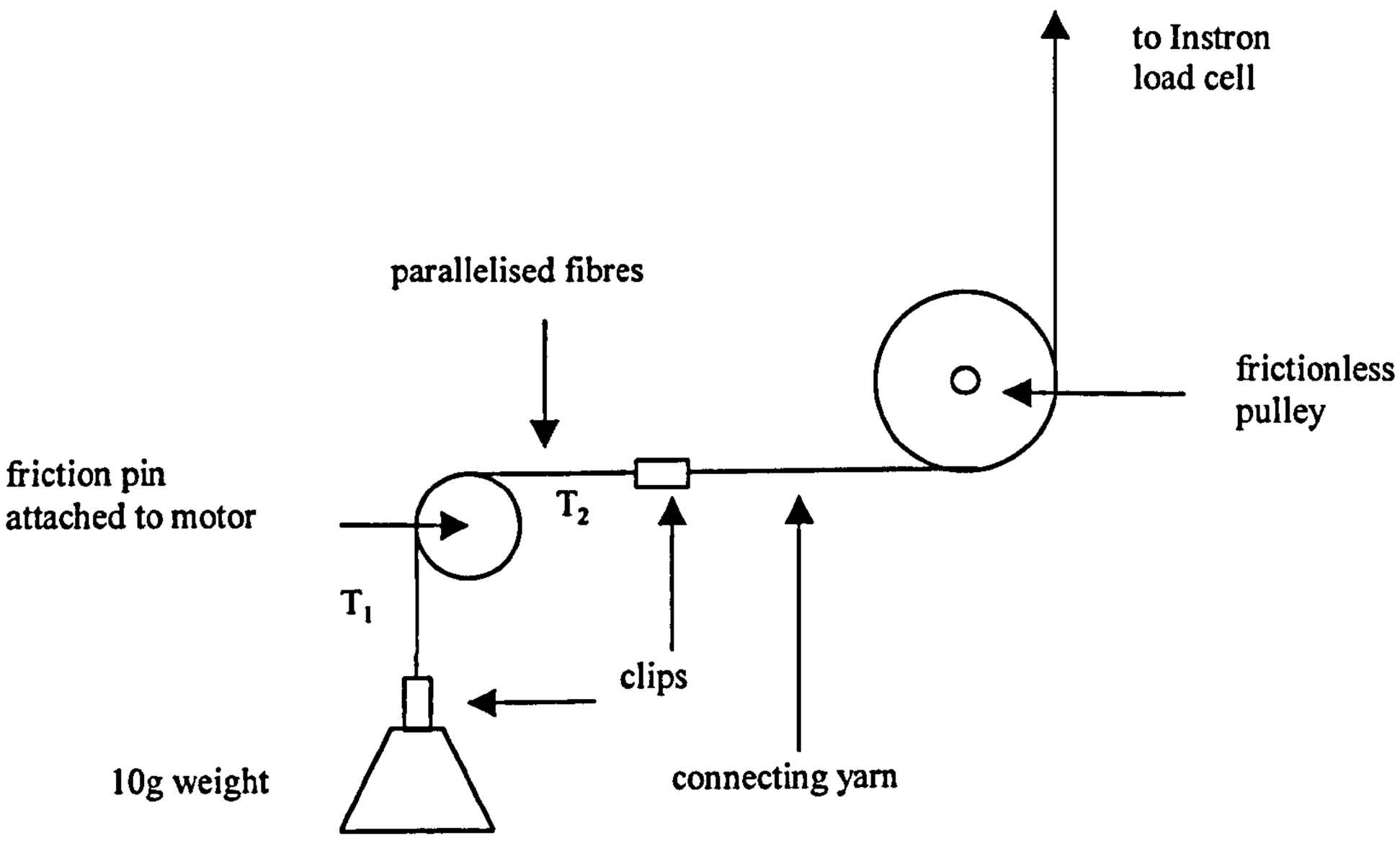


Figure 2.6 Friction Measuring Arrangement

The friction force is measured by the value of T_2, which is determined by mounting the pin assembly on an Instron (6021), draping a section of finished tow (~0.05g) over the pin and recording the tension force in the connecting yarn. The friction pin was 8mm in diameter and was made from stainless steel. It was originally a component from a Rothschild yarn friction testing machine. A scanning electron microscope (SEM) image

of the friction pin surface is shown in Figure 2.7. This was produced on a Hitachi S3200N microscope.

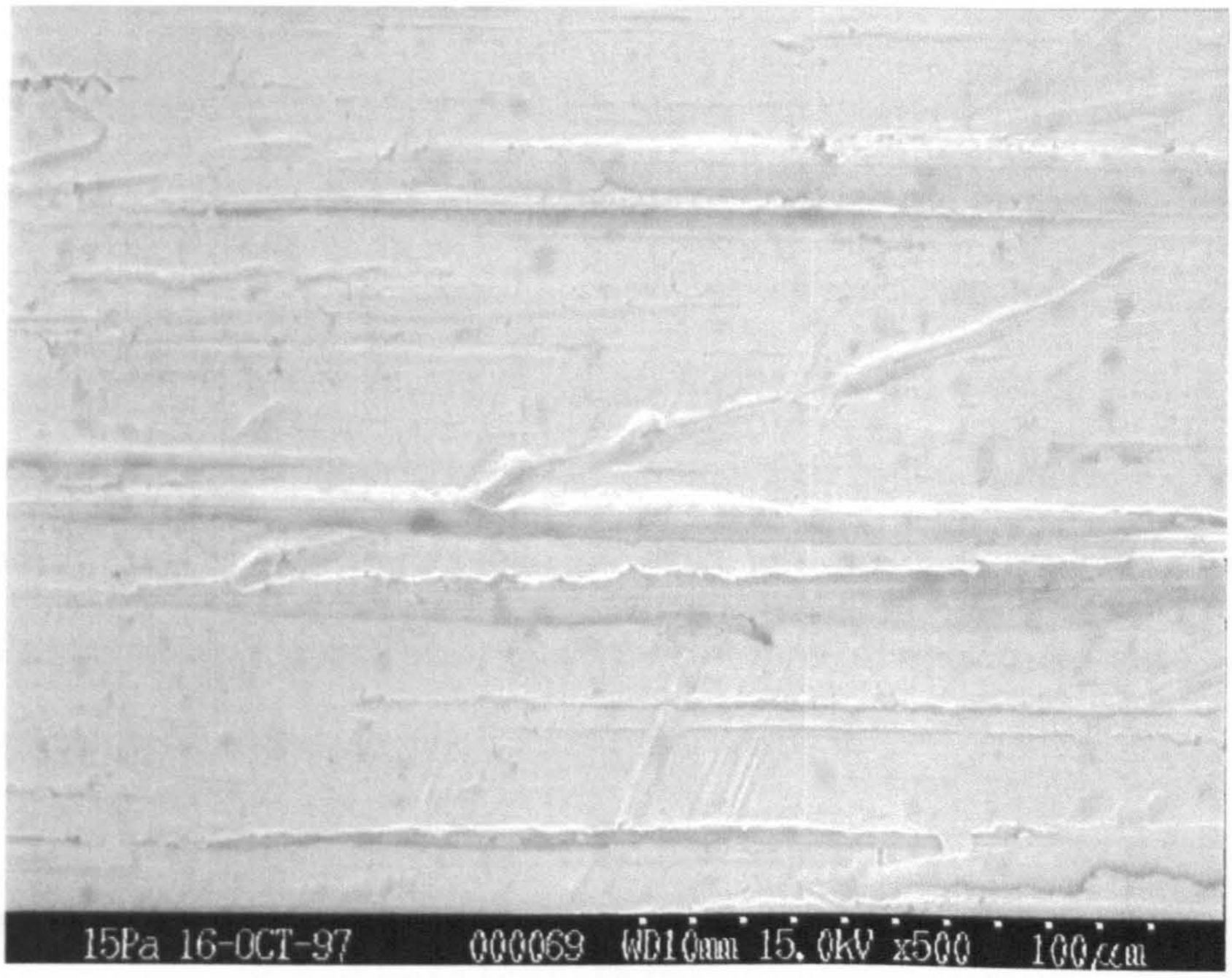


Figure 2.7 Stainless Steel Friction Pin Surface

The image gives an indication of the pin roughness from the dimensions of the surface features, although it is not possible to deduce the average height of the asperities from this micrograph. The direction of pin rotation corresponds to the horizontal direction in Figure 2.7.

When fibre/fibre friction was measured, a section of tow was wrapped around the pin and fixed at both ends before a second piece of tow was draped over the covered pin.

T_1 was taken to be 10.17cN, which comprises the 10g weight, a clip (0.34g), and half of the weight of the fibres (0.025g), giving a total weight of 10.365g, which is multiplied by the acceleration due to gravity (9.81 ms^{-2}) to give a force.

Static and dynamic friction forces were measured on the finished viscose tow from treatments 1 to 11, shown in Table 2.1, section 2.1.1.2. Static friction was measured with the friction pin stationary and the minimum Instron cross-head speed of 0.1 mm/min. Dynamic friction was measured by setting the pin rotating with a surface speed of 0.5 m/s. The cross-head speed was negligible in the dynamic experiments. Five repeat measurements were made on each tow when determining fibre/metal friction. For fibre/fibre friction three repeats were done, changing the tows wrapped around and draped over the pin before each measurement.

2.2.2 Results and Discussion

2.2.2.1 Fibre/Metal Friction

Five quantities were measured from each friction trace. T2statmin and T2statmax are the minimum and maximum static friction forces (in cN) averaged over several stick/slip peaks. T2del is the difference between the maximum and minimum friction forces, associated with stick-slip behaviour (Bowden and Tabor, 1950b). T2dyn0 and T2dyn5 are dynamic friction forces (in cN) measured as soon as the pin is set to rotate and after five minutes. The two dynamic friction forces were measured because the value changes with time. This effect was also observed by Amirbayat and Cooke (1989), who found in their experiments that the biggest change in friction occurred over the first ten minutes of sliding. A typical friction chart from the present work is shown in Figure 2.8. Both static (saw tooth) and dynamic (smooth) traces are shown on the same chart. The static trace runs off the end of the right hand side of the chart and reappears on the left (the experiments were not interrupted).

The scales on the x and y axes are time (min) and force (cN) respectively. The scale markers visible on the plot correspond to 5 minutes and 50cN. This particular trace was derived from unfinished viscose.

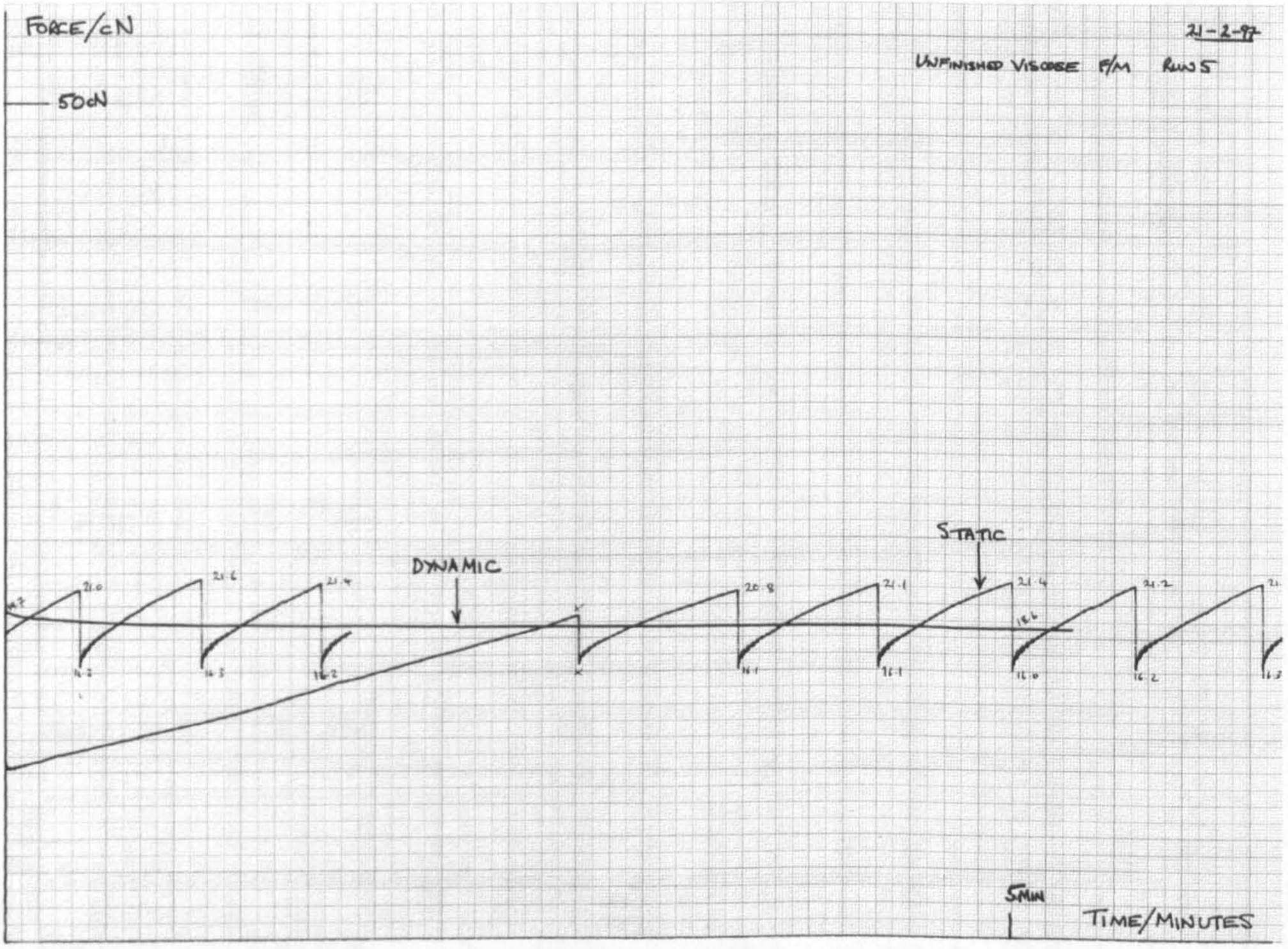


Figure 2.8 Fibre/Metal Friction Trace from Instron and Pin Experiment

Friction results are shown in Table 2.5. Data from unfinished tow are included for comparison.

Table 2.5 Fibre/Metal Friction Forces (in cN)

Sample	Date	run	T2statmin	T2statmax	T2del	T2dyn0	T2dyn5
Unfinished	21/02/97	1	16.5	27.3	10.8	19.7	19.5
		2	17.5	26.1	8.6	19.8	19.5
		3	16.1	24.4	8.3	19.4	18.9
		4	15.2	24.8	9.6	19.8	19
		5	16.2	21.3	5.1	19.7	18.6
Sample 1	19/12/96	1	13.4	15.4	2.0	16.6	17
		2	13.5	15.7	2.2	17.0	16.8
		3	14.3	15.8	1.5	18.9	18
		4	13.4	16.3	2.9	17.6	17
		5	14.1	16.3	2.2	17.2	17.4
Sample 2	20/12/96	1	12.2	12.9	0.7	17.0	16.8
		2	13	13	0.0	16.4	16.4
		3	13.3	13.8	0.5	16.7	16.5
		4	13.5	13.9	0.4	16.8	16.5
		5	13.2	13.9	0.7	16.3	16.2
Sample 3	18/12/96	1	13.8	16.4	2.6	17.4	17.6
		2	13.4	16.2	2.8	18.6	17.7
		3	14	15.8	1.8	18.0	17.8
		4	13.8	15.9	2.1	17.4	17.1
		5	13.5	16.4	2.9	17.6	17.4
Sample 4	19/12/96	1	12.9	16.7	3.8	17.2	16.6
		2	13.1	17.9	4.8	18.2	17
		3	13.7	17.8	4.1	18.6	17.6
		4	13	17.2	4.2	19.2	17.4
		5	12.7	16.9	4.2	18.4	17.3
Sample 5	19/12/96	1	13.3	14.9	1.6	15.6	15.4
		2	13.8	14.4	0.6	15.2	15.2
		3	13.1	14.6	1.5	14.9	14.9
		4	13.9	15.5	1.6	15.5	16
		5	12.5	13.5	1.0	14.4	15
Sample 6	20/12/96	1	13.5	13.5	0.0	14.9	15.5
		2	13.2	14.1	0.9	16.5	16.7
		3	12.7	13.7	1.0	16.0	16.5
		4	13.4	13.9	0.5	16.4	16.7
		5	13.2	13.2	0.0	16.2	16.4
Sample 7	20/12/96	1	14.1	15.3	1.2	17.8	17.4
		2	13.5	15.6	2.1	17.4	17
		3	13.1	15.5	2.4	17.4	16.7
		4	14.2	15.8	1.6	17.2	16.8
		5	13.4	14	0.6	16.0	16.6
Sample 8	18/12/96	1	12.8	15.6	2.8	16.7	16.6
		2	12.3	13.9	1.6	16.6	16.2
		3	13.3	15.2	1.9	16.4	16.4
		4	12.7	14	1.3	15.7	16
		5	12.4	13.2	0.8	15.8	15.8

Table 2.5 Continued

Sample	Date	run	T2statmin	T2statmax	T2del	T2dyn0	T2dyn5
Sample 9	18/12/96	1	12.6	15.1	2.5	15.5	15.8
		2	12.7	14.4	1.7	15.6	15.8
		3	13.2	14.8	1.6	15.8	16.1
		4	12.5	14.8	2.3	15.6	15.6
		5	13.2	15.6	2.4	15.7	15.8
Sample 10	19/12/96	1	13	14.4	1.4	15.0	16
		2	13.4	14.7	1.3	15.3	15.8
		3	14.1	15.2	1.1	16.4	16.7
		4	13.6	15	1.4	16.0	16.6
		5	13.1	14.9	1.8	16.0	16.2
Sample 11	18/12/96	1	13.9	17	3.1	17.0	16.6
		2	13.3	15.8	2.5	16.0	16.3
		3	13.4	15.1	1.7	15.8	16
		4	13.1	14.6	1.5	15.6	16.2
		5	13.1	13.8	0.7	15.8	16

Statistical Analysis of the Fibre/Metal Friction Data

The fibre/metal friction data from the finished samples, produced for the designed experiment (see section 2.1), were analysed to determine the main effects on friction of the deposition variables, and of the interaction terms (cross products of variables). The deposition variables (factors) were %092:P2DL in the emulsion (A), emulsion concentration (B), deposition temperature (C) and deposition time (D).

Half-normal plots show whether a factor is significant in determining an effect (in this case friction forces). Factors which lie on or close to the half-normal line are random and could be generated by error. Factors well away from the line are significant. In some cases interpretation might not be straightforward, since departure from the line may be open to subjective interpretation. The reader is referred to Caulcutt (1995) for further guidance on interpreting half-normal plots. Average friction results over five replicates are used in the analyses shown here.

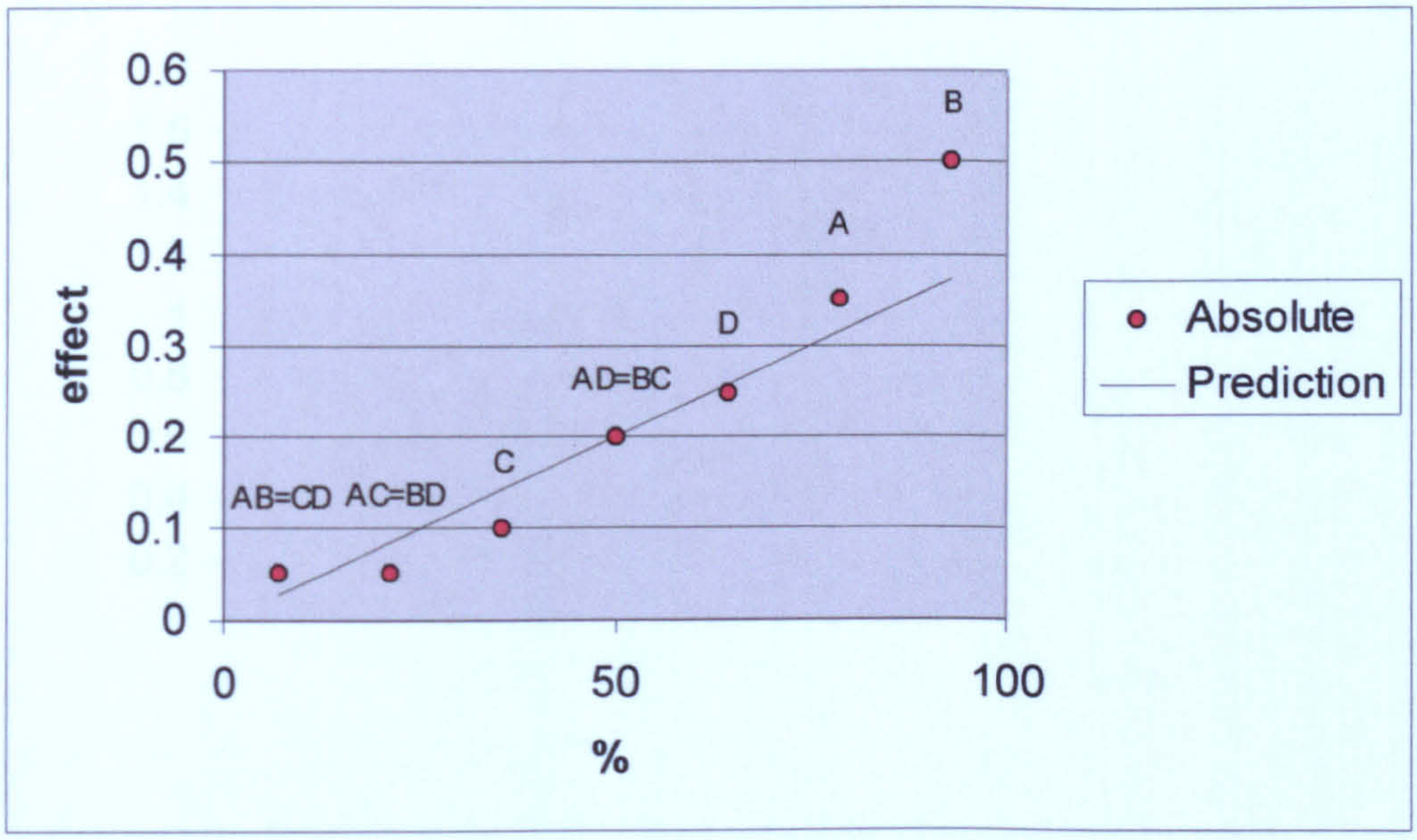


Figure 2.9 Half-normal Plot for T2statmin (Fibre/Metal)

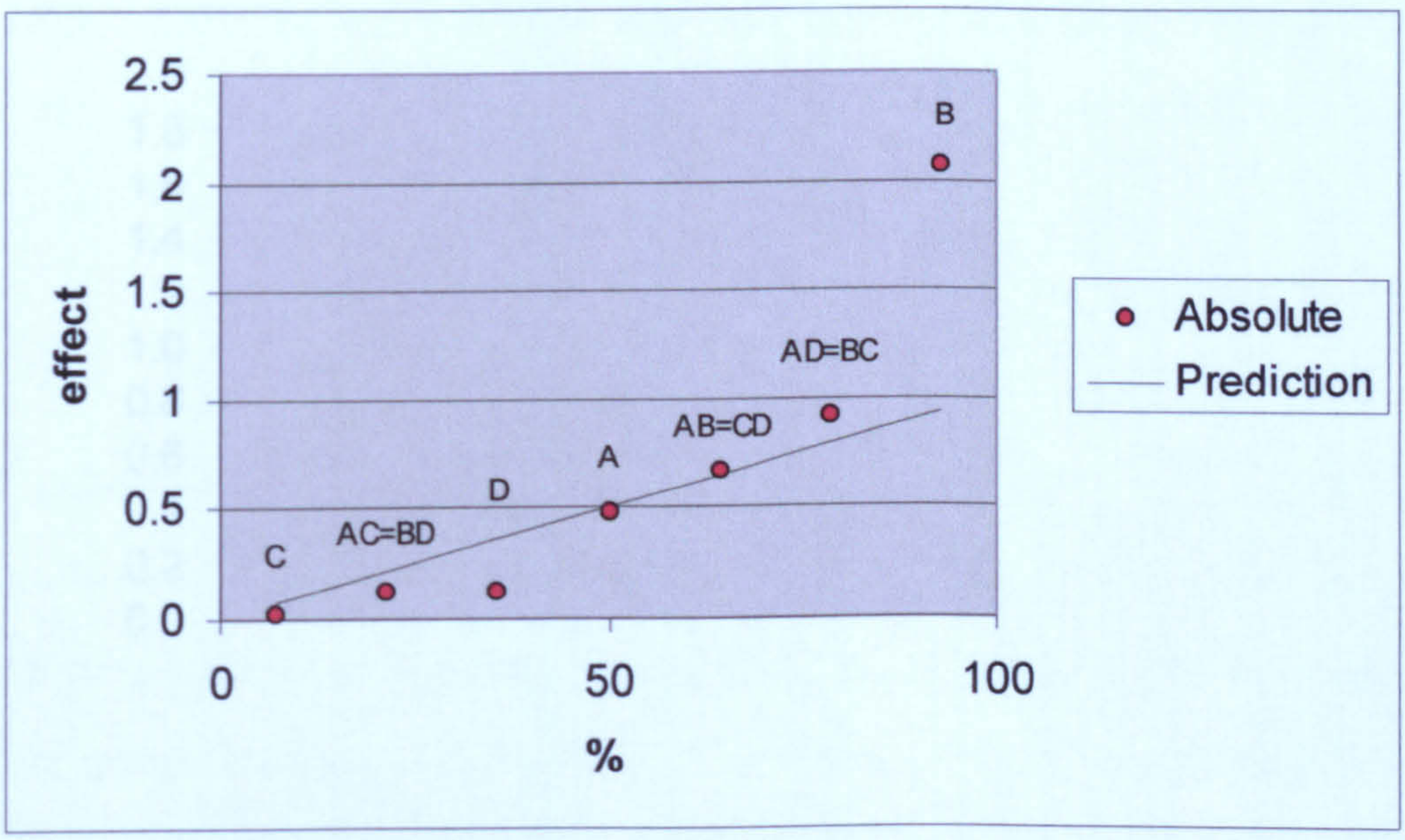


Figure 2.10 Half-normal Plot for T2statmax (Fibre/Metal)

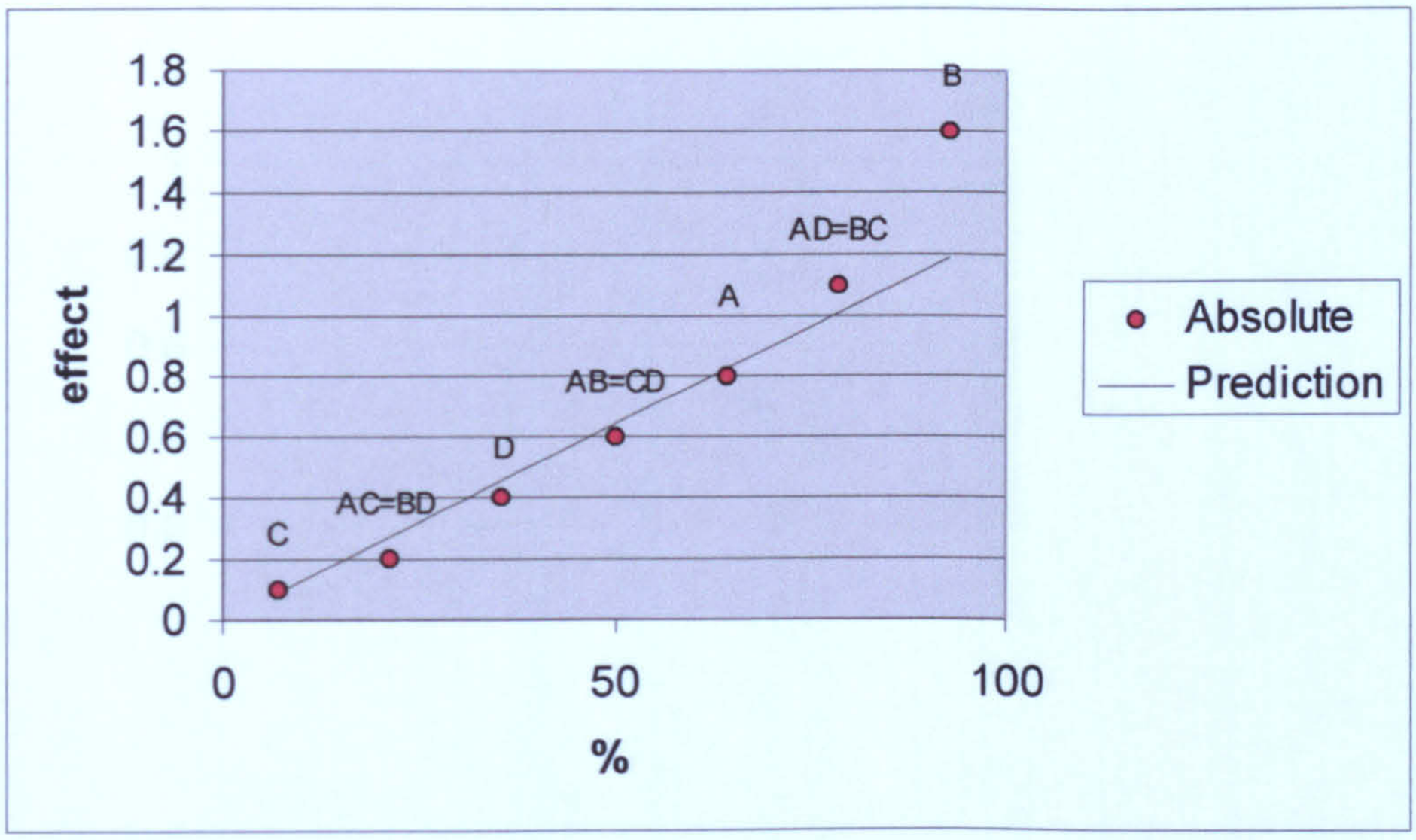


Figure 2.11 Half-normal Plot for T2del (Fibre/Metal)

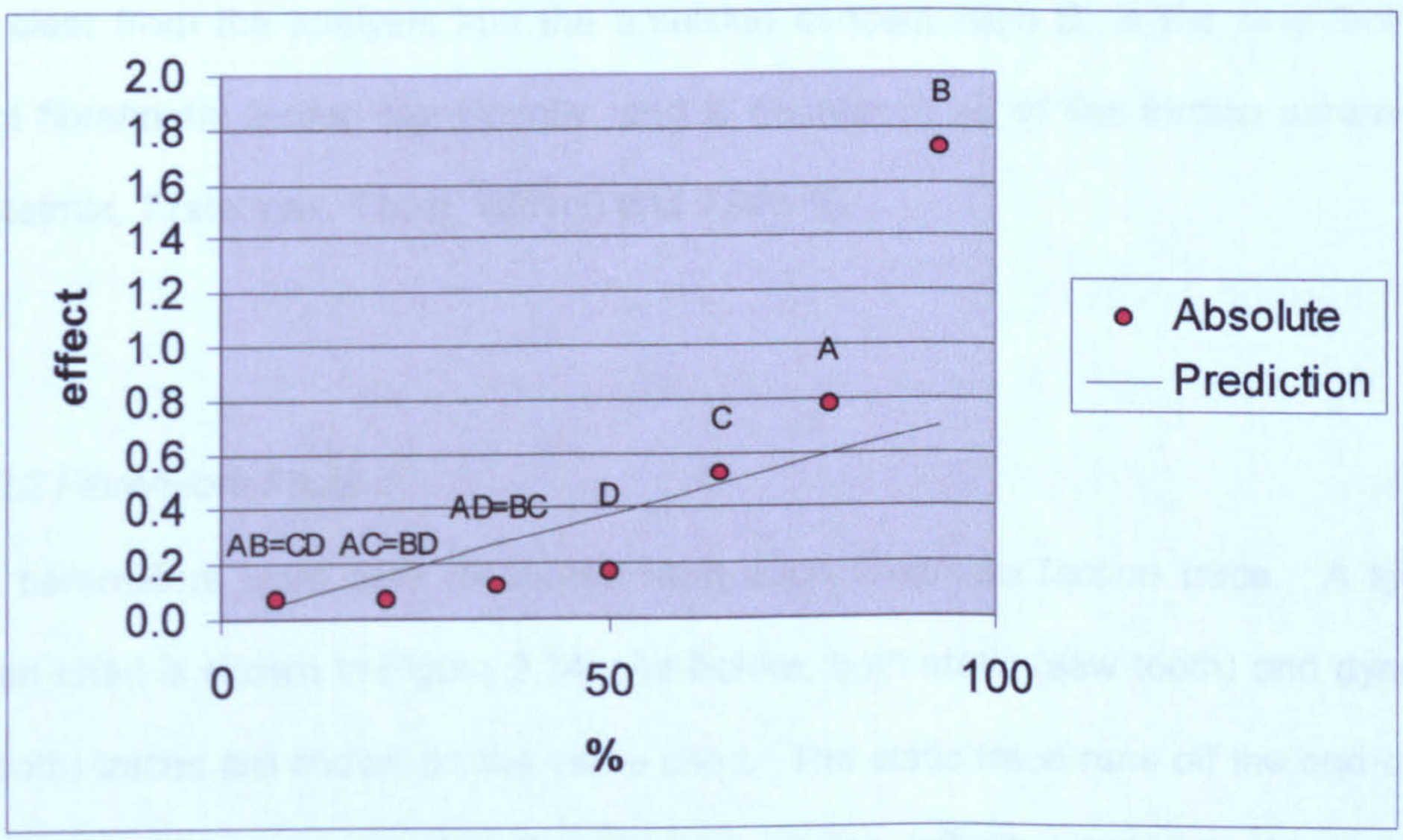


Figure 2.12 Half-normal Plot for T2dyn0 (Fibre/Metal)

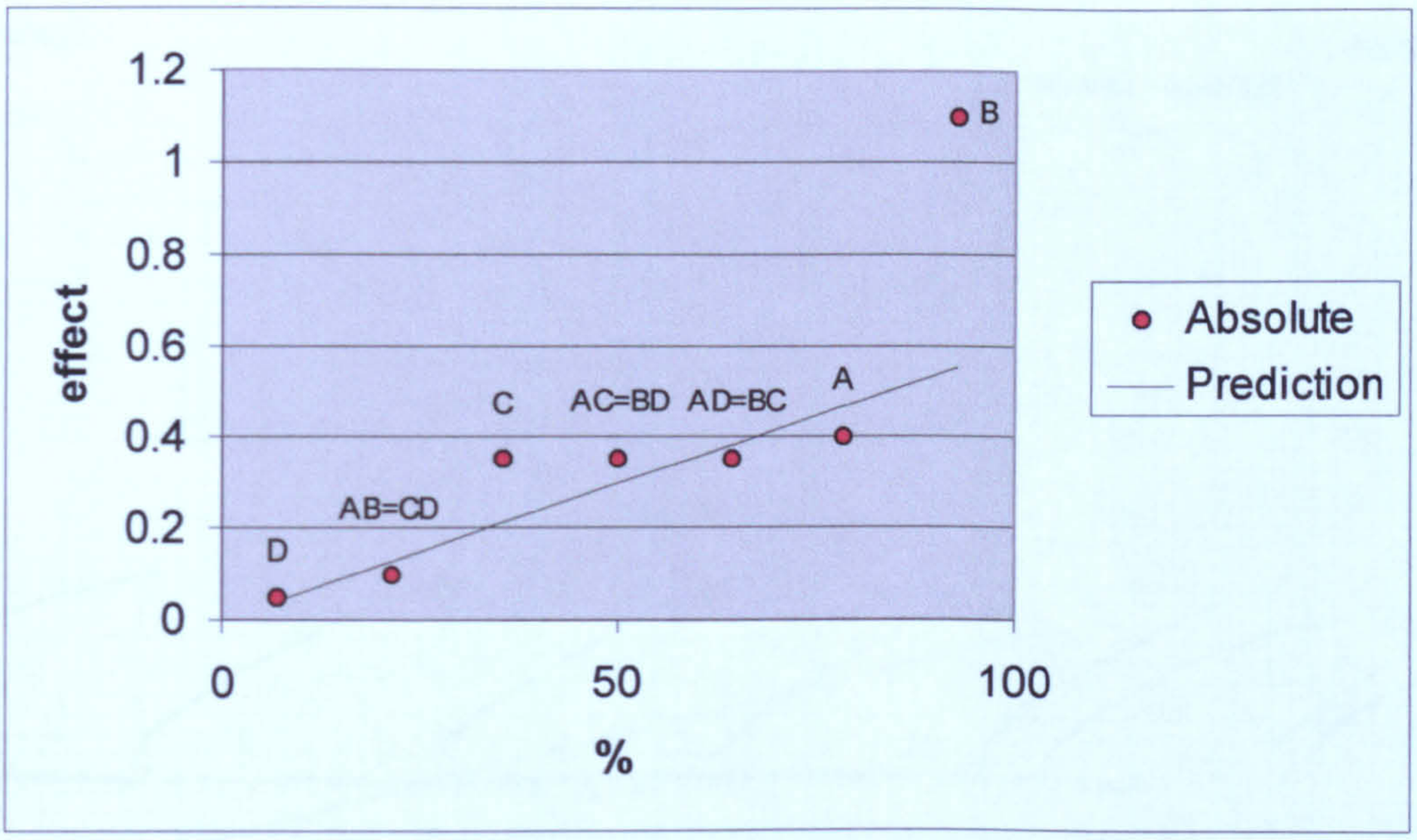


Figure 2.13 Half-normal Plot for T2dyn5 (Fibre/Metal)

It is clear from the analysis that the emulsion concentration B, is the only factor to affect fibre/metal friction significantly, and B decreases all of the friction parameters (T2statmin, T2statmax, T2del, T2dyn0 and T2dyn5).

2.2.2.2 Fibre/Fibre Friction

Five parameters were also measured from each fibre/fibre friction trace. A typical friction chart is shown in Figure 2.14. As before, both static (saw tooth) and dynamic (smooth) traces are shown on the same chart. The static trace runs off the end of the right hand side of the chart and reappears on the left (the experiments were not interrupted). The scales on the x and y axes are time (min) and force (cN) respectively. The scale markers visible on the plot correspond to 5 minutes and 50cN. This trace was derived from unfinished viscose.

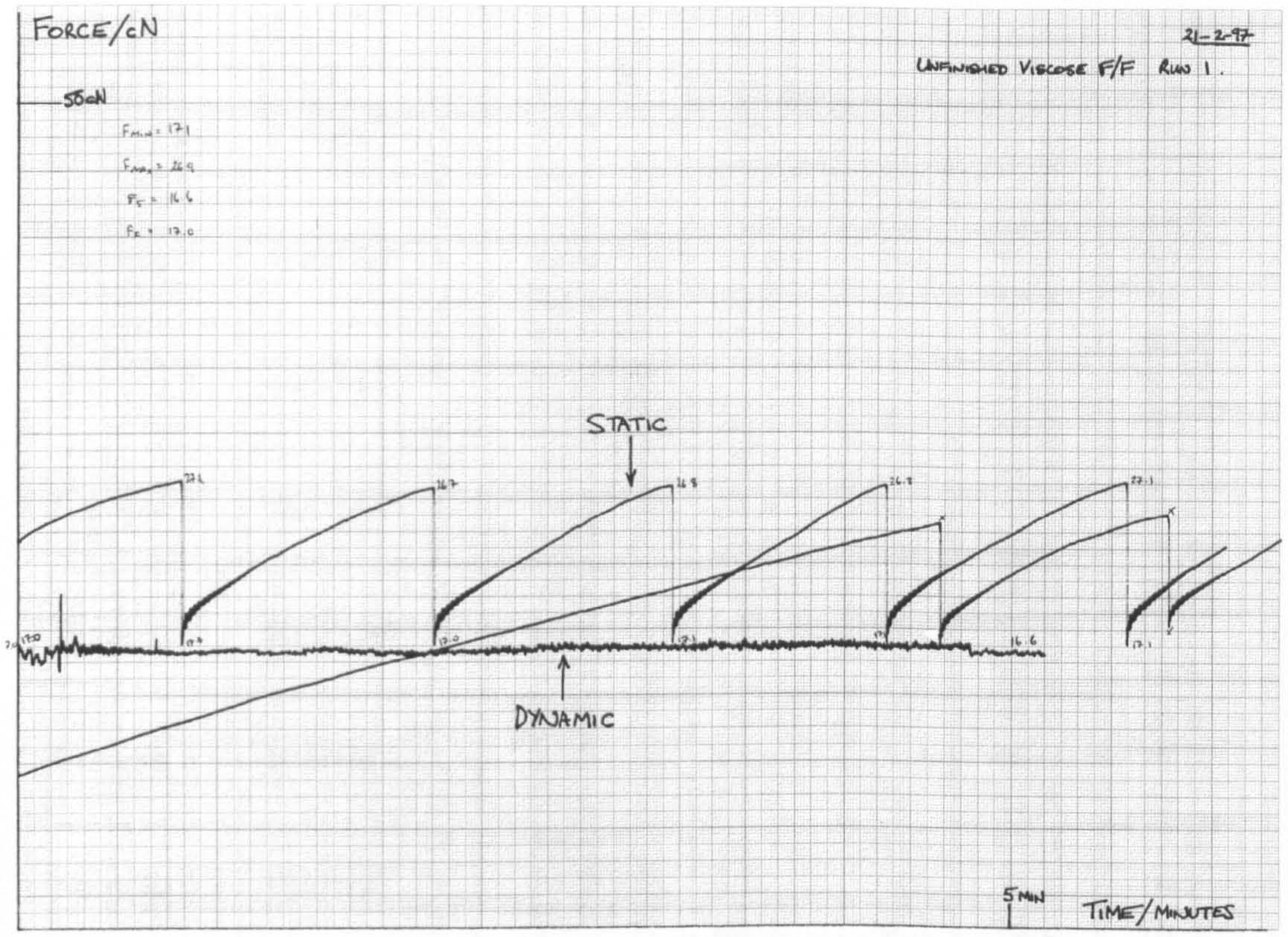


Figure 2.14 Fibre/Fibre Friction Trace from Instron and Pin Experiment

As before, T2statmin and T2statmax are the minimum and maximum static friction forces (in cN), T2del is the difference between the maximum and minimum friction forces, and T2dyn0 and T2dyn5 are dynamic friction forces (also in cN), measured as soon as the pin is set to rotate, and after five minutes respectively. The difference between fibre/fibre maximum and minimum, static friction forces (T2del) has been associated with the crunching sound made when bundles of fibres are compressed. It is termed as 'scroop' (Broughton Jr. and El Mogahzy, 1993). A summary of the friction data is given in Table 2.6.

Table 2.6 Fibre/Fibre Friction Forces (in cN)

Sample	Date	run	T2statmin	T2statmax	T2del	T2dyn0	T2dyn5
Unfinished	21/02/97	1	17.1	26.9	9.8	17.0	16.6
		2	15.1	27.6	12.5	17.2	17.0
		3	16.9	30.9	14.0	17.5	18.0
Sample 1	15/01/97	1	14.4	30.9	16.5	15.6	15.5
		2	14.1	30.2	16.1	18.4	18.7
		3	15.1	30.9	15.8	16.0	16.2
Sample 2	16/01/97	1	13.9	27.5	13.6	19.0	22.0
		2	13.8	30.1	16.3	16.2	16.7
		3	14.1	25.7	11.6	20.4	24.0
Sample 3	15/01/97	1	14.3	29.4	15.1	17.2	17.9
		2	15.1	27.6	12.5	18.0	18.4
		3	14.4	30.6	16.2	16.5	16.9
Sample 4	16/01/97	1	13.4	28.8	15.4	17.5	17.6
		2	13.5	27.2	13.7	16.5	16.5
		3	13.5	30.2	16.7	15.6	15.8
Sample 5	16/01/97	1	15.3	26.7	11.4	16.0	16.0
		2	14.5	29.9	15.4	15.8	15.7
		3	16.5	31.5	15.0	18.0	17.9
Sample 6	16/01/97	1	14.7	30.2	15.5	17.6	16.2
		2	15.5	28.8	13.3	16.2	15.9
		3	14.8	31.4	16.6	18.0	17.6
Sample 7	16/01/97	1	14.5	29.3	14.8	16.9	17.0
		2	14.6	27.5	12.9	15.7	15.6
		3	15.0	28.6	13.6	15.3	15.5
Sample 8	15/01/97	1	17.5	26.2	8.7	17.5	18.2
		2	14.0	22.0	8.0	16.2	16.9
		3	14.5	25.5	11.0	18.2	18.8
Sample 9	15/01/97	1	14.5	26.5	12.0	18.2	17.5
		2	15.7	30.4	14.7	16.5	16.5
		3	14.0	32.0	18.0	15.7	15.8
Sample 10	15/01/97	1	15.9	28.3	12.4	17.2	18.0
		2	14.3	28.9	14.6	18.0	18.0
		3	15.5	31.7	16.2	16.5	16.7
Sample 11	15/01/97	1	15.0	30.4	15.4	16.8	16.5
		2	14.5	30.3	15.8	17.3	17.5
		3	16.0	27.6	11.6	18.0	17.0

Statistical Analysis of the Fibre/Fibre Friction Data

The fibre/fibre friction data were analysed to determine the main effects on friction of the deposition variables, and of the interaction terms (cross products of variables). As before, the deposition variables (factors) were %092:P2DL in the emulsion (A), emulsion concentration (B), deposition temperature (C) and deposition time (D).

Again half-normal plots show whether a factor is significant in determining an effect (friction forces in this work) and factors which lie on or close to the half-normal line are random and could be generated by error. Factors away from the line are significant. Difficulties with interpretation and deciding whether a factor lies far enough from the half-normal line to be considered significant, are commented on in section 2.2.2.1. The average friction results over three replicates are used in these analyses.

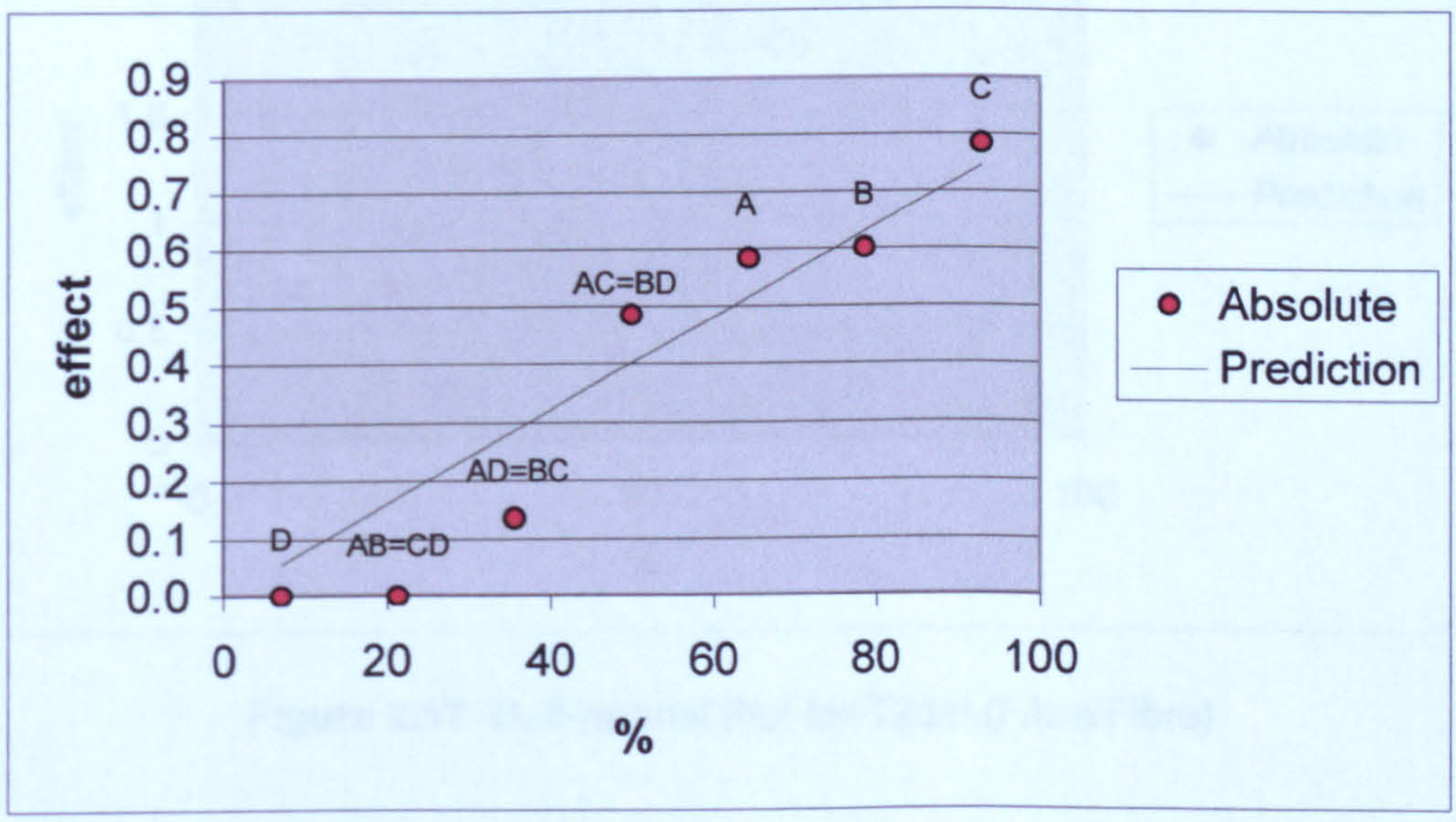


Figure 2.15 Half-normal Plot for T2statmin (Fibre/Fibre)

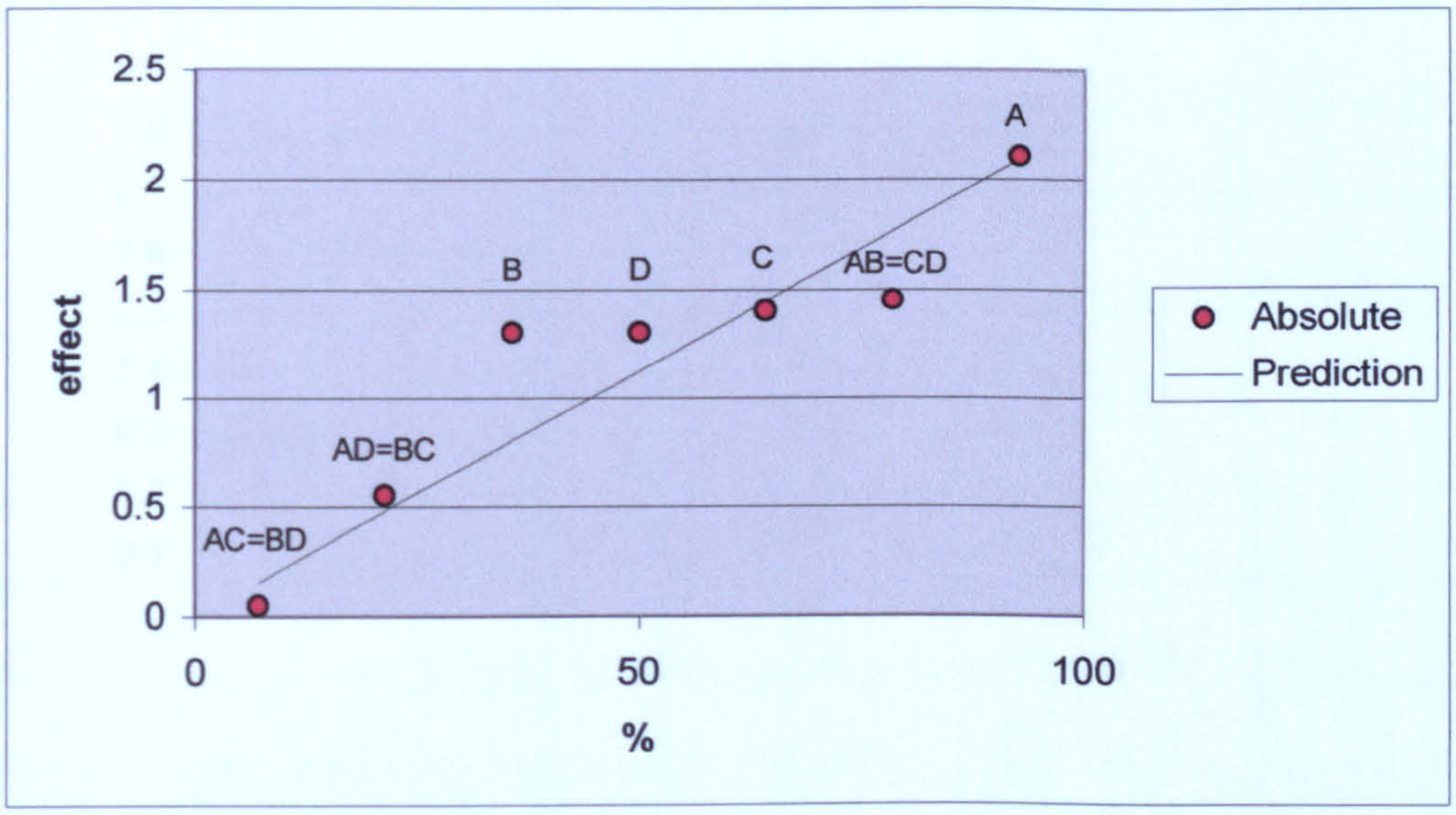


Figure 2.16 Half-normal Plot for T2statmax (Fibre/Fibre)

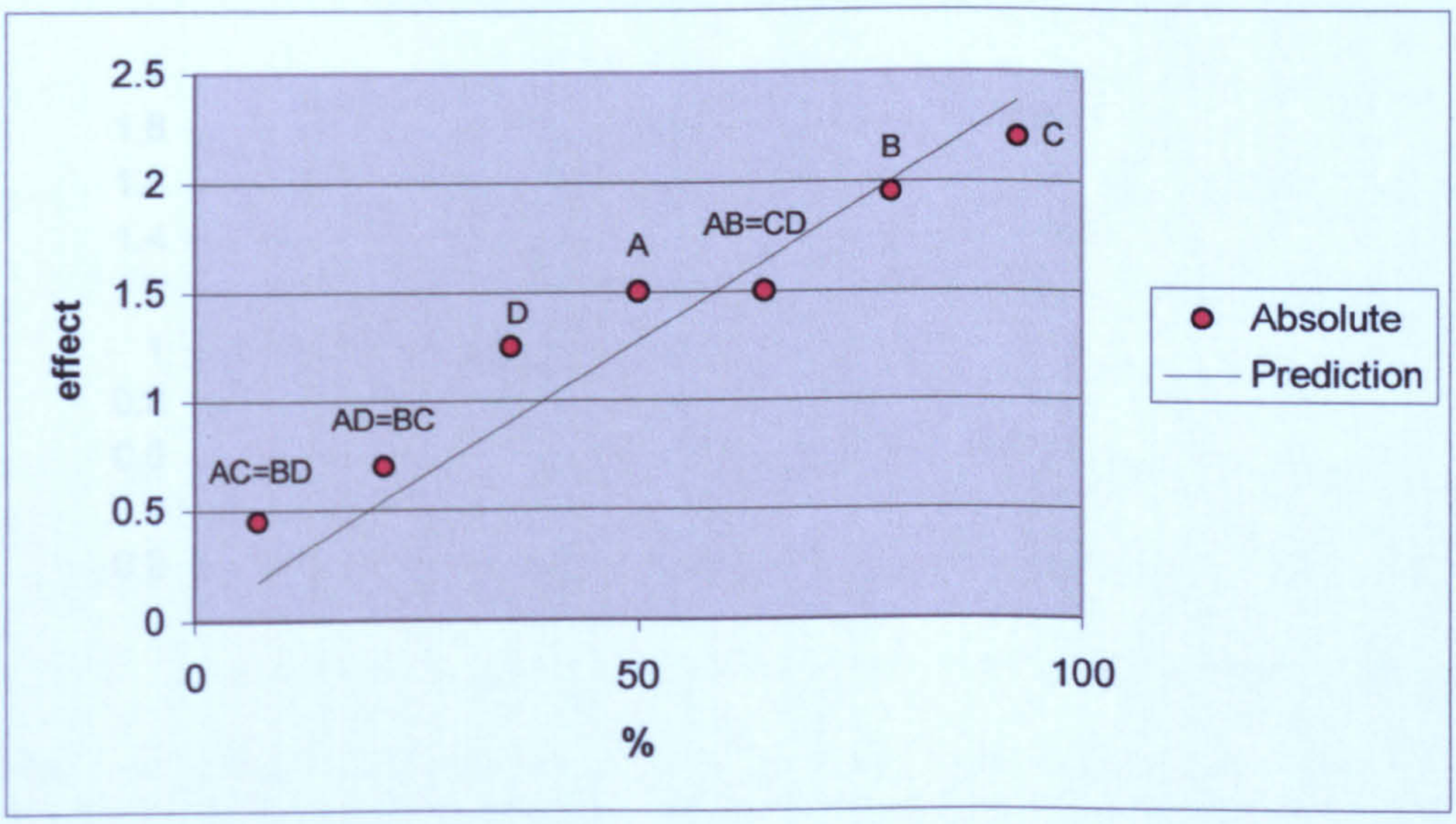


Figure 2.17 Half-normal Plot for T2del (Fibre/Fibre)

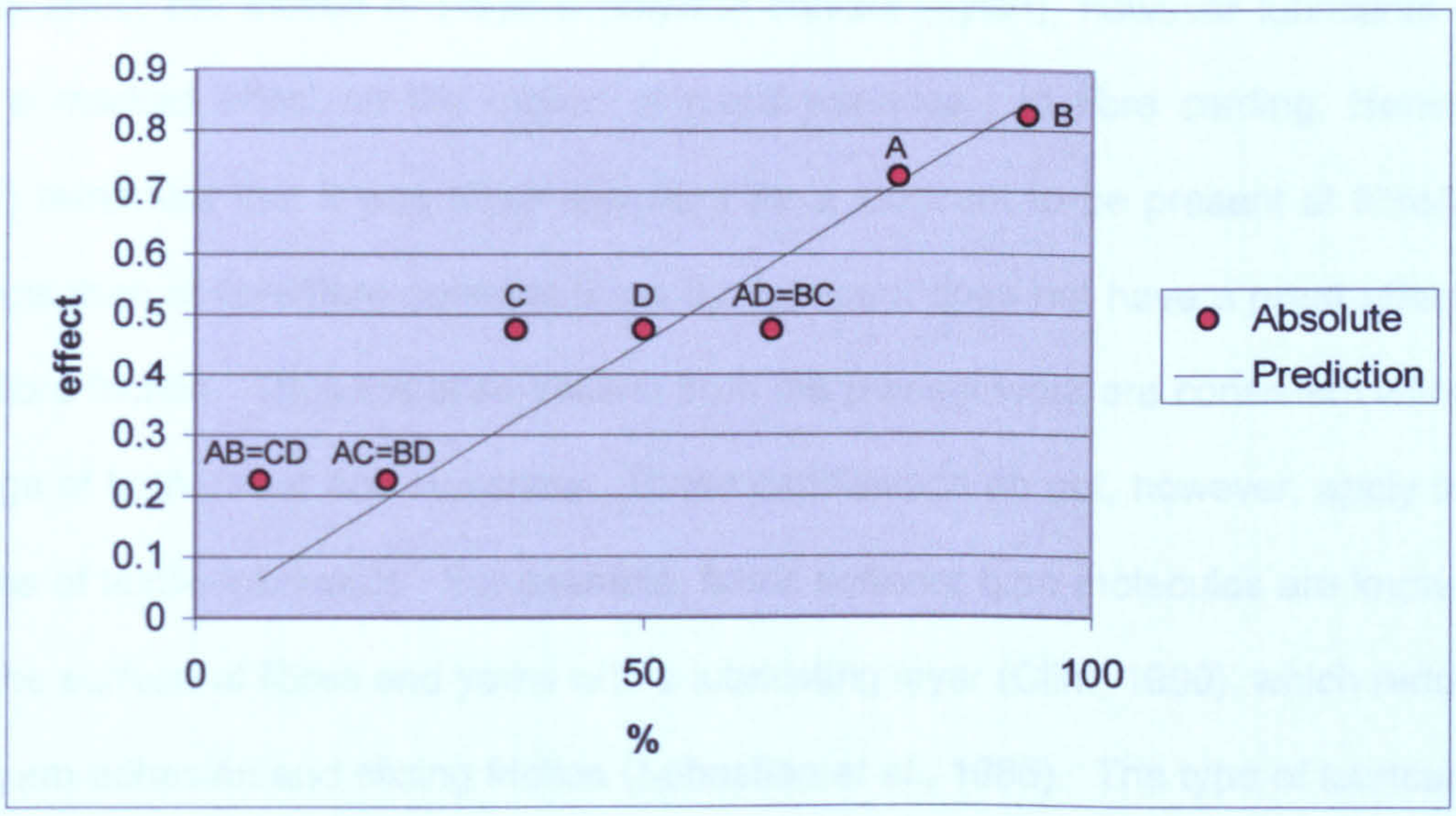


Figure 2.18 Half-normal Plot for T2dyn0 (Fibre/Fibre)

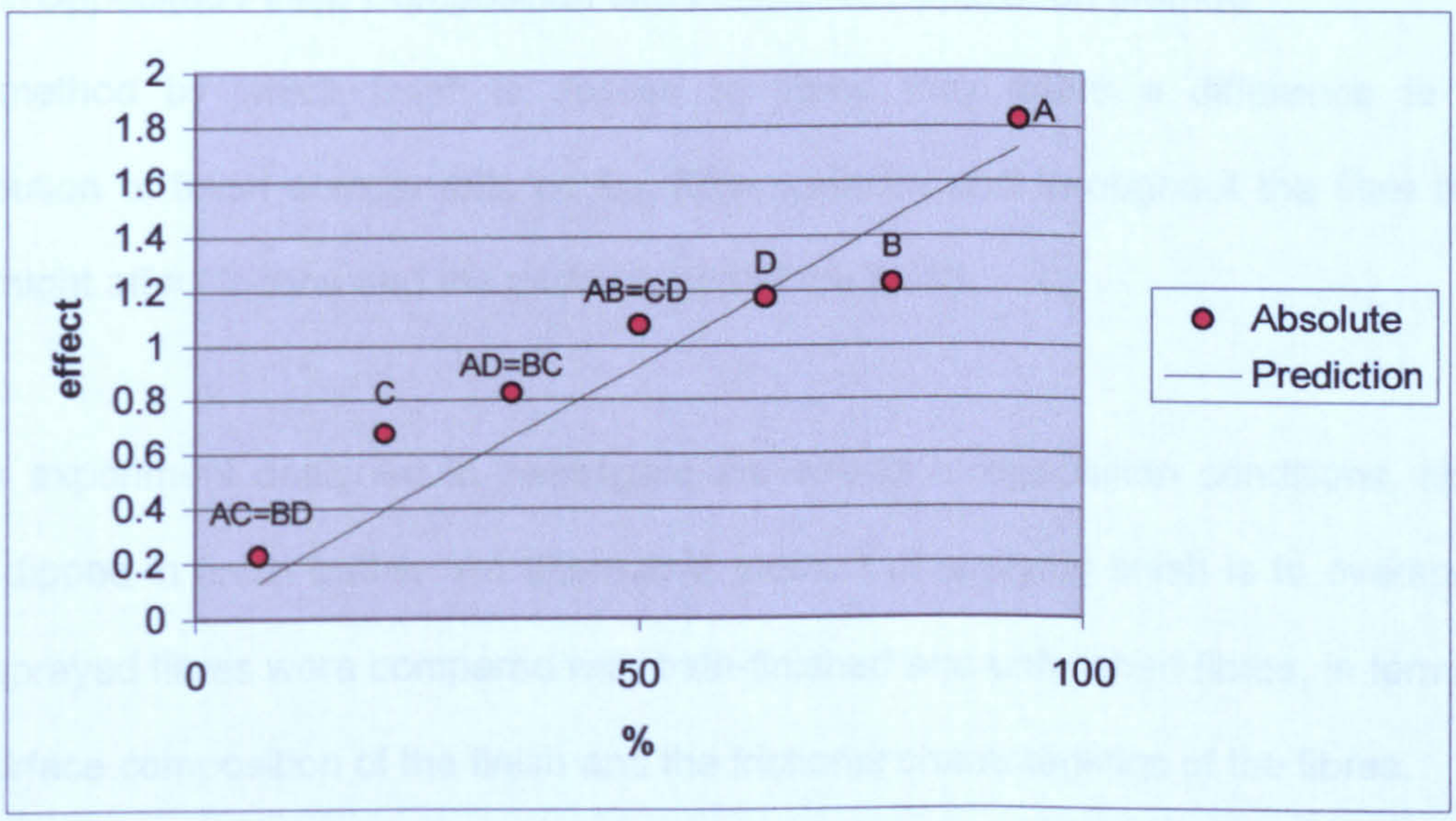


Figure 2.19 Half-normal Plot for T2dyn5 (Fibre/Fibre)

The conclusion from Figures 2.15 to 2.19 is that unlike fibre/metal friction, fibre/fibre friction is not affected significantly by the deposition variables, i.e. %092:P2DL in the emulsion (A), emulsion concentration (B), deposition temperature (C) and deposition time (D). This is in agreement with Tabor (1960), who observed that lubricants did not

greatly affect the friction of polymer/polymer contact (nylon), however lubricants can have a marked effect on the friction of metal surfaces. In fibre carding, Henshaw (1961) remarked that it was more important for a lubricant to be present at fibre/wire contacts than at fibre/fibre contacts since the lubricant does not have a great effect on fibre/fibre friction. Thus the observations from the present work are consistent with the findings of both Tabor and Henshaw. These conclusions do not, however, apply to all classes of textile lubricants. For example, fabric softener type molecules are known to coat the surface of fibres and yarns with a lubricating layer (Clint, 1990), which reduces inter-yarn adhesion and sliding friction (Sebastian *et al.*, 1986). The type of lubricant is therefore important.

2.2.2.3 Deposited Finish Composition and Friction vs Application Method

The method by which finish is applied to fibres may make a difference to the distribution of finish components on the fibre surfaces and throughout the fibre bulk. This might affect friction and the performance of the finish.

In the experiment designed to investigate the effects of deposition conditions, fibres were dipped in finish baths. An alternative method of applying finish is to overspray. Oversprayed fibres were compared with bath-finished and unfinished fibres, in terms of the surface composition of the finish and the frictional characteristics of the fibres.

In overspray 1 (os1) 15g of cleaned viscose tow (as used in previous experiments) was dipped in distilled water, in order to wet the fibres. The wet tow was mangled then sprayed (hand held spray bottle) with 10ml of a 5 gl^{-1} emulsion of P2DL/092 (90:10). The fibres were mangled again to remove excess liquid, then dried in an oven at 110°C for 30 minutes.

The method for overspray 2 (os2) was the same as for os1, but 50ml of a $2gl^{-1}$ was spray applied with the same P2DL/092 ratio. Drying conditions were also the same.

The oversprays were intended to represent application of a small volume of finish (os1) against a larger volume of more dilute finish (os2), although the actual quantity of surfactants applied to the fibres from os2 was double that applied from os1.

Deposited Finish Composition

Three sections from each oversprayed tow were removed and analysed by SIMS. Spectra were recorded from five regions on each section and the %092 relative to P2DL, at the surface, was calculated using the model described in section 2.1.2.1.

Table 2.7 Surface Composition Results for Oversprayed Viscose Fibres

Specimen	Section	Result no.	092Ratio	%092surf
Overspray 1	1	1	0.163	0.82
		2	0.154	0.64
		3	0.181	1.25
		4	0.21	2.13
		5	0.182	1.28
	2	6	0.164	0.85
		7	0.133	0.31
		8	0.204	1.93
		9	0.141	0.42
		10	0.235	3.07
	3	11	0.052	0.16
		12	0.345	9.27
		13	0.215	2.30
		14	0.308	6.81
		15	0.309	6.87

Table 2.7 Continued

Specimen	Section	Result no.	092Ratio	%092surf
Overspray 2	1	1	0.136	0.35
		2	0.221	2.52
		3	0.341	8.99
		4	0.159	0.74
		5	0.119	0.15
	2	6	0.062	0.08
		7	0.119	0.15
		8	0.09	0.00
		9	0.027	0.48
		10	0.129	0.26
	3	11	0.218	2.41
		12	0.217	2.38
		13	0.213	2.23
		14	0.268	4.58
		15	0.131	0.28

Table 2.7 shows the mean %092 at the fibre surfaces compared to P2DL. Means, standard deviations and CV% values were calculated from the data in Table 2.8.

Table 2.8 Average Surface Composition of Oversprayed Viscose Fibres

Specimen	Mean %092 at surface	Standard Deviation	CV%
os1	2.5	2.8	111
os2	1.7	2.4	142

The %092 at the surface is compared to the % extract (i.e. total finish on fibre) and the %092 in the extract in Table 2.9.

Table 2.9 Comparison of Bulk and Surface Finish Compositions of Oversprayed Viscose Tow

Specimen	%extract	%092 in extract	%092 at surface
os1	0.2	8.0	2.5
os2	0.3	6.0	1.7

Both oversprayed emulsions contained the same ratio of 092/P2DL (10:90). Table 2.9 suggests that the more concentrated overspray (os1) gave a higher %092 at the surface and in the bulk than the dilute overspray (os2), but when the two data sets of surface composition were t-tested, there was not a significant difference (95% confidence) between the two oversprays. The surface composition was similar and the distribution of 092 relative to P2DL was poor (CV%>100%) for both os1 and os2.

The presence of a 149 amu peak, which corresponds to cellulose, was noted in the SIMS spectra of the oversprayed samples (Figures 2.20a and 2.20b). Cellulose, from unfinished regions of fibre, could perturb the relative yield of secondary ions from P2DL and 092. This effect was commented on by Reed (1989) and it could invalidate the model, used in the present work to calculate surface composition (see sections 2.1.2.1 and 2.1.2.2). Furthermore, some regions of the os2 specimen were found to be contaminated with poly(dimethyl siloxane) (PDMS) which would make determination of the surface composition even less reliable. There is not enough evidence from the SIMS analysis of the two oversprayed samples to say that the composition of finish on their surfaces was significantly different.

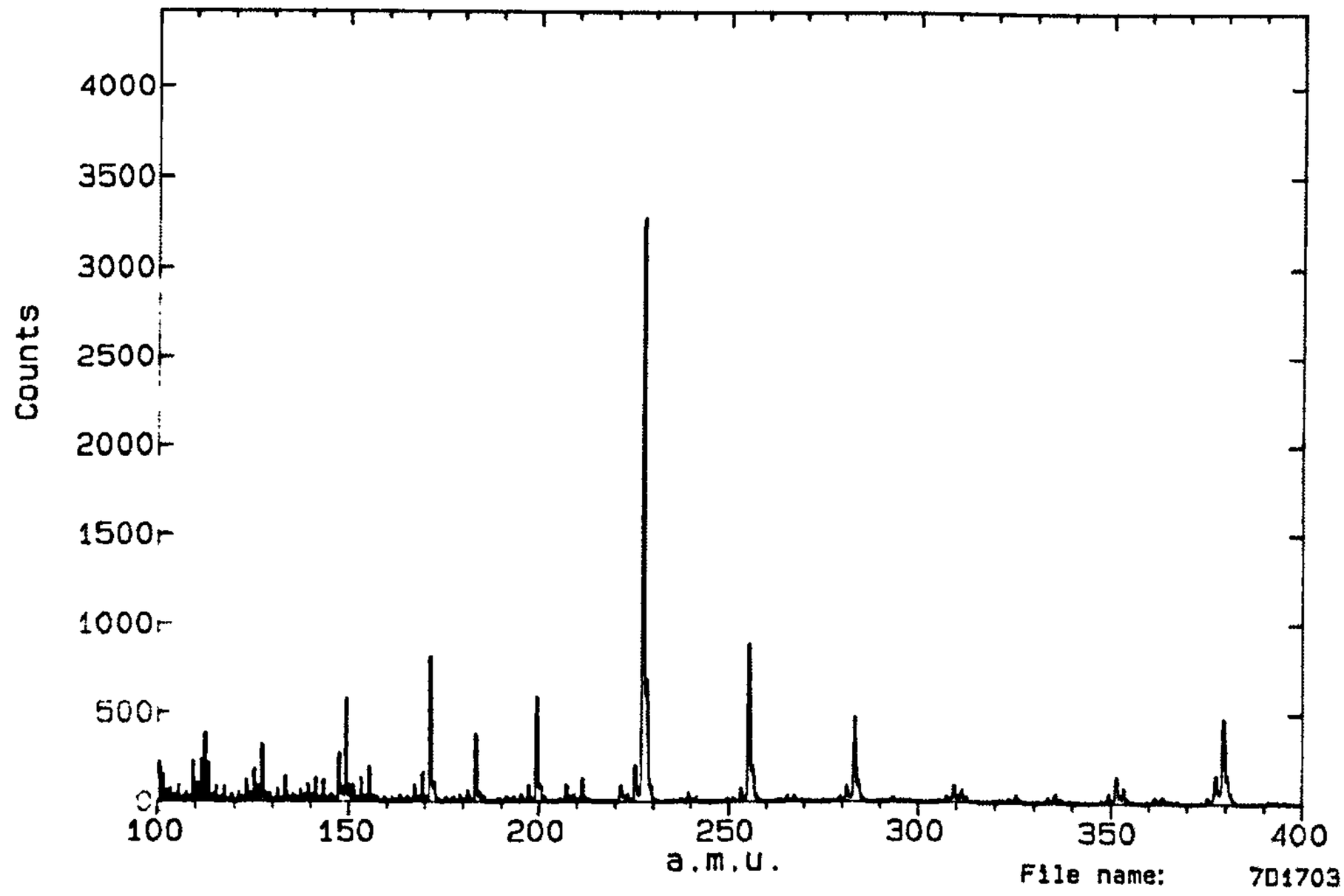


Figure 2.20a SIMS Spectrum of Overspray 1 on Viscose

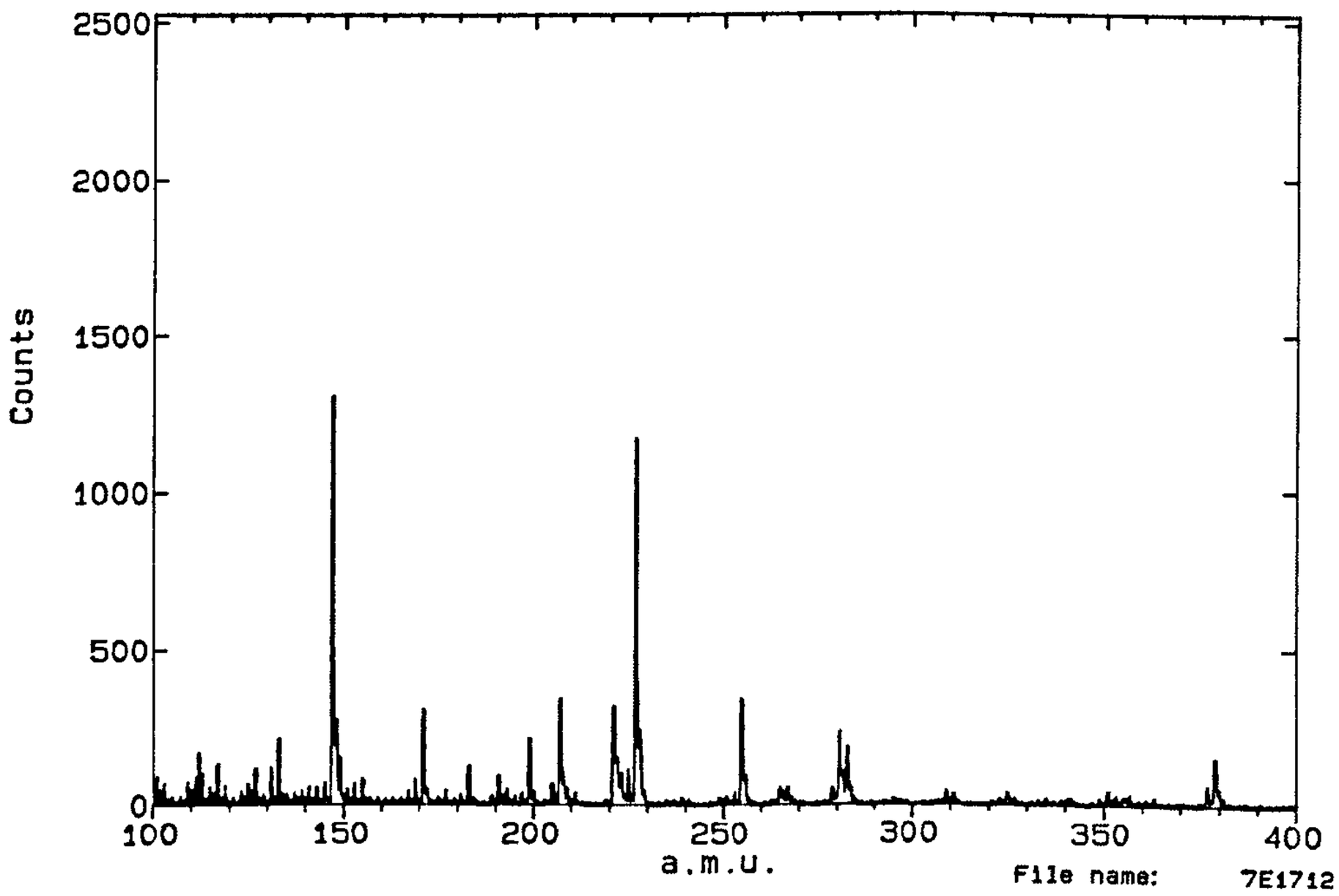


Figure 2.20b SIMS Spectrum of Overspray 2 on Viscose

The total amount of surfactant sprayed onto the fibres from os2 was double that of os1 and this accounts for the higher %extract from os2. If all of the applied finish remained on the sprayed fibres, finish levels of 0.33% and 0.67% would be expected for os1 and os2 respectively. The actual quantity of finish on fibre was less than the expected maximum for both treatments, and the % extract from os2 was less than double that of os1. Some finish may have evaporated during drying and it appears that there are differences in the quantity lost, depending on whether the finish emulsion is dilute or concentrated. Also, there may have been some loss of finish in the liquor mangled from the oversprayed fibres. The maximum adsorption of some surfactants onto viscose can be rapid, i.e. in less than a minute (Jacobasch *et al.*, 1972), however, surfactant mixtures adsorbed onto solid surfaces can take many hours to reach equilibrium (Schwuger and Smolka, 1977). It is possible that the finish mixture sprayed onto the fibre had not reached equilibrium adsorption and some of the 092 and P2DL remained in the liquor removed from the fibres during mangling.

Friction

Friction values for os1 and os2 were measured by same method as used previously (see section 2.2.1).

Table 2.10 Fibre/Metal Friction Forces of Oversprayed Viscose Tow (in cN)

Sample	Date	run	T2statmin	T2statmax	T2del	T2dyn0	T2dyn5
Overspray 1	31/05/97	1	13.2	16.4	3.2	18.2	17.5
		2	14.1	18.7	4.6	18.9	17.8
		3	13.8	19.3	5.5	17.9	17.3
		4	13.6	17.8	4.2	17.7	17.3
		5	14	16.9	2.9	17.8	17.4
Overspray 2	07/06/97	1	14.3	17.6	3.3	19.0	18.1
		2	13.8	17.1	3.3	18.2	17.2
		3	13.7	16	2.3	16.8	17.1
		4	13.5	15.9	2.4	17.0	17
		5	14.1	16	1.9	17.7	17.3

Table 2.11 Fibre/Fibre Friction Forces for Oversprayed Viscose Tow (in cN)

Sample	Date	run	T2statmin	T2statmax	T2del	T2dyn0	T2dyn5
Overspray 1	07/06/97	1	14.7	28.6	13.9	16.0	16.0
		2	14.8	28.8	14.0	16.6	16.8
		3	14.5	28.7	14.2	15.7	15.5
Overspray 2	07/06/97	1	13.8	27.8	14.0	15.3	15.8
		2	15.2	28.3	13.1	16.0	16.3
		3	14.3	25.3	11.0	16.0	16.6

2.2.3 Statistical Comparison of All Friction Data

Friction results from the designed experiment, together with oversprayed and unfinished viscose, were subjected to analysis of variance (ANOVA) tests. Using the ANOVA output, Duncan's new multiple range test (Statistics for Industry, 1996) was used to group similar friction results and to show which were different at the 5% significance level. The bands show which results overlap and are not significantly different. For example, in Table 2.12, samples 8, 9, 2, 4, 6 and 5 are grouped and do not differ (5% significance). Other groups are shown and there is some overlap, however, the unfinished sample stands alone and is significantly different from all of the other finished fibres. The friction forces shown in Tables 2.12 to 2.21 are the averages of the results shown in Tables 2.5, 2.6, 2.10 and 2.11 (all forces are in cN).

2.2.3.1 Comparison of Fibre/Metal Friction Results (Tables 2.12 to 2.16)

Table 2.12 Grouping of T2statmin Results (Fibre/Metal)

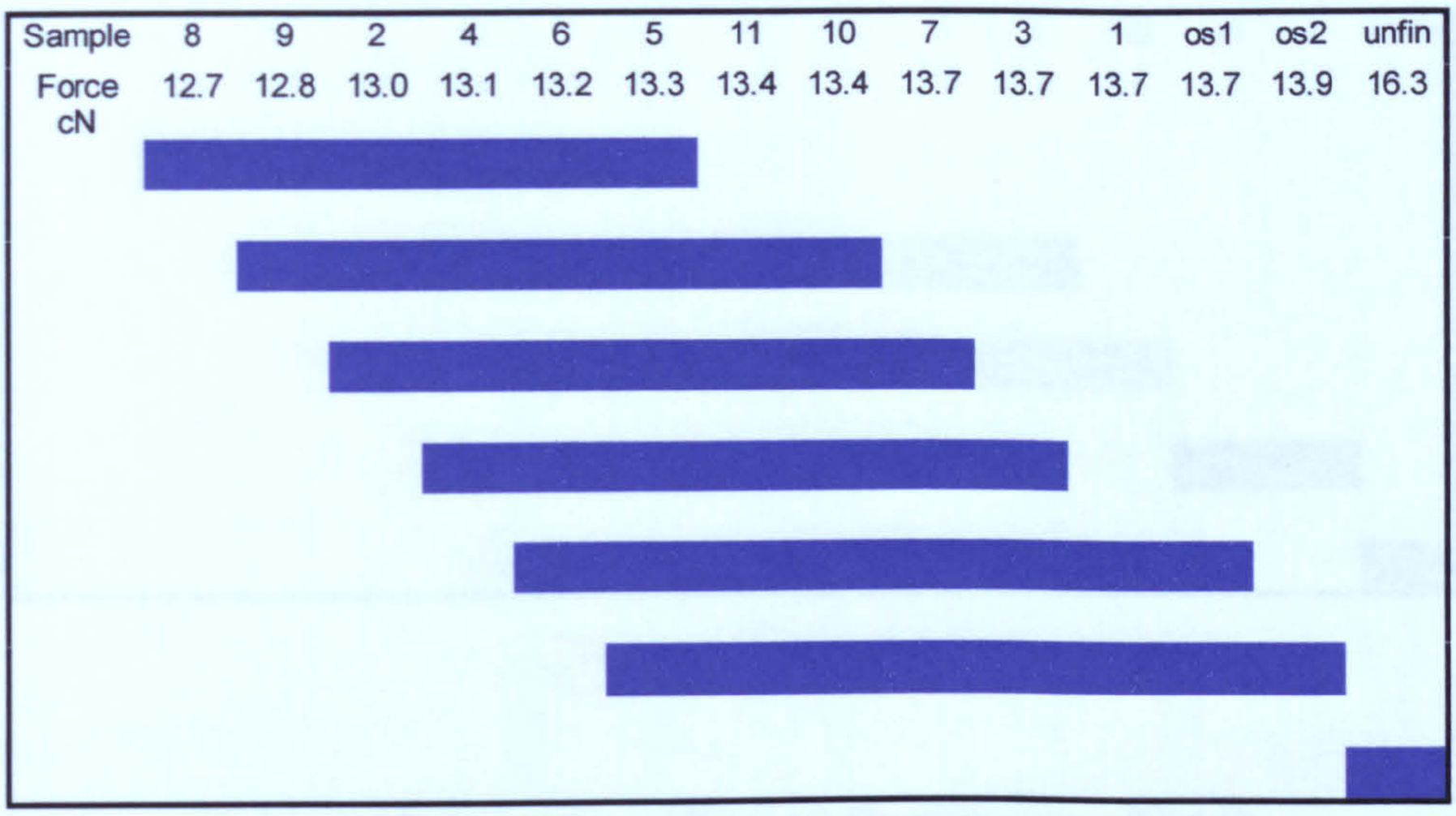


Table 2.13 Grouping of T2statmax Results (Fibre/Metal)

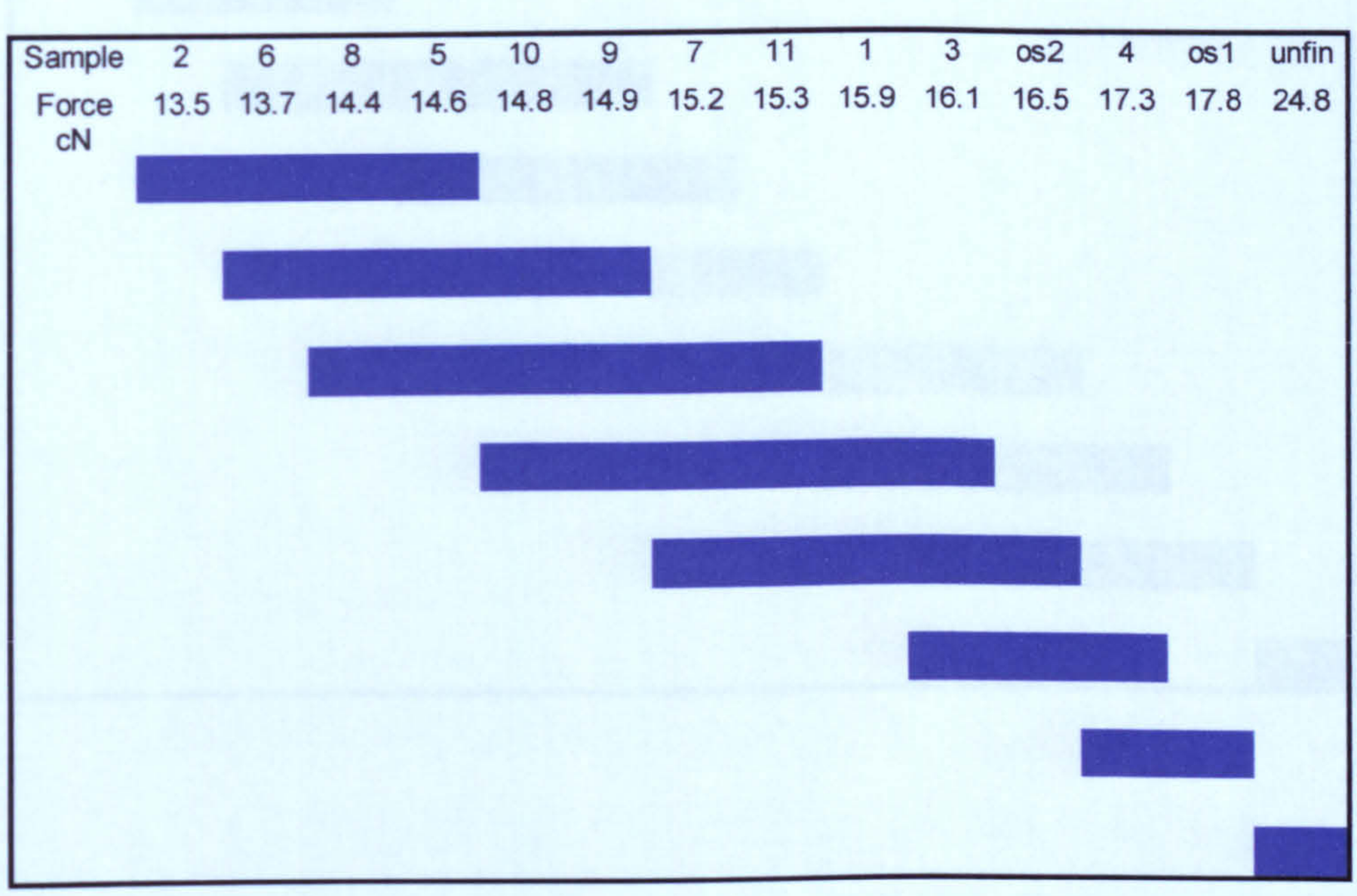


Table 2.14 Grouping of T2del Results (Fibre/Metal)

Sample	2	6	5	10	7	8	11	9	1	3	os2	os1	4	Unfin
Force cN	0.5	0.5	1.3	1.4	1.6	1.7	1.9	2.1	2.2	2.4	2.6	4.1	4.2	8.5

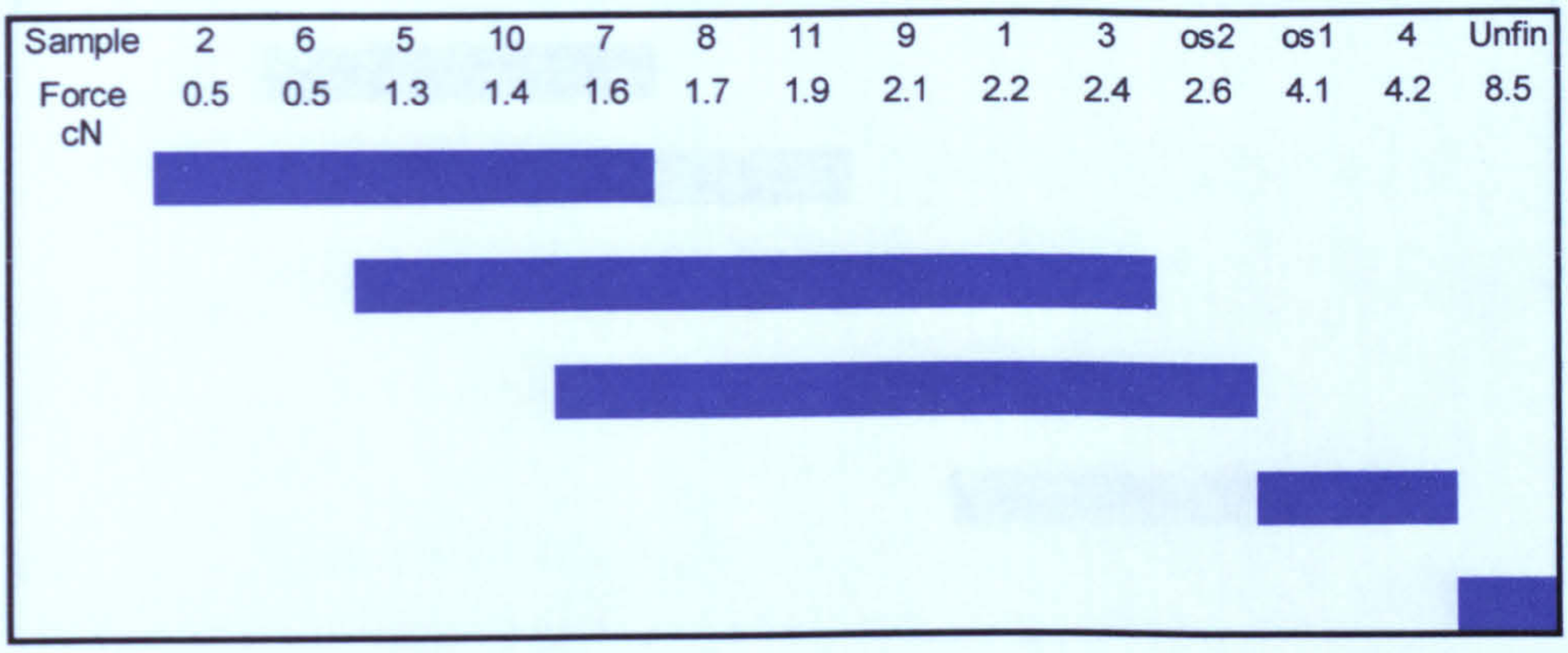


Table 2.15 Grouping of T2dyn0 Results (Fibre/Metal)

Sample	5	9	10	6	11	8	2	7	1	os2	3	os1	4	unfin
Force cN	15.1	15.6	15.7	16.0	16.0	16.2	16.6	17.2	17.5	17.7	17.8	18.1	18.3	19.7

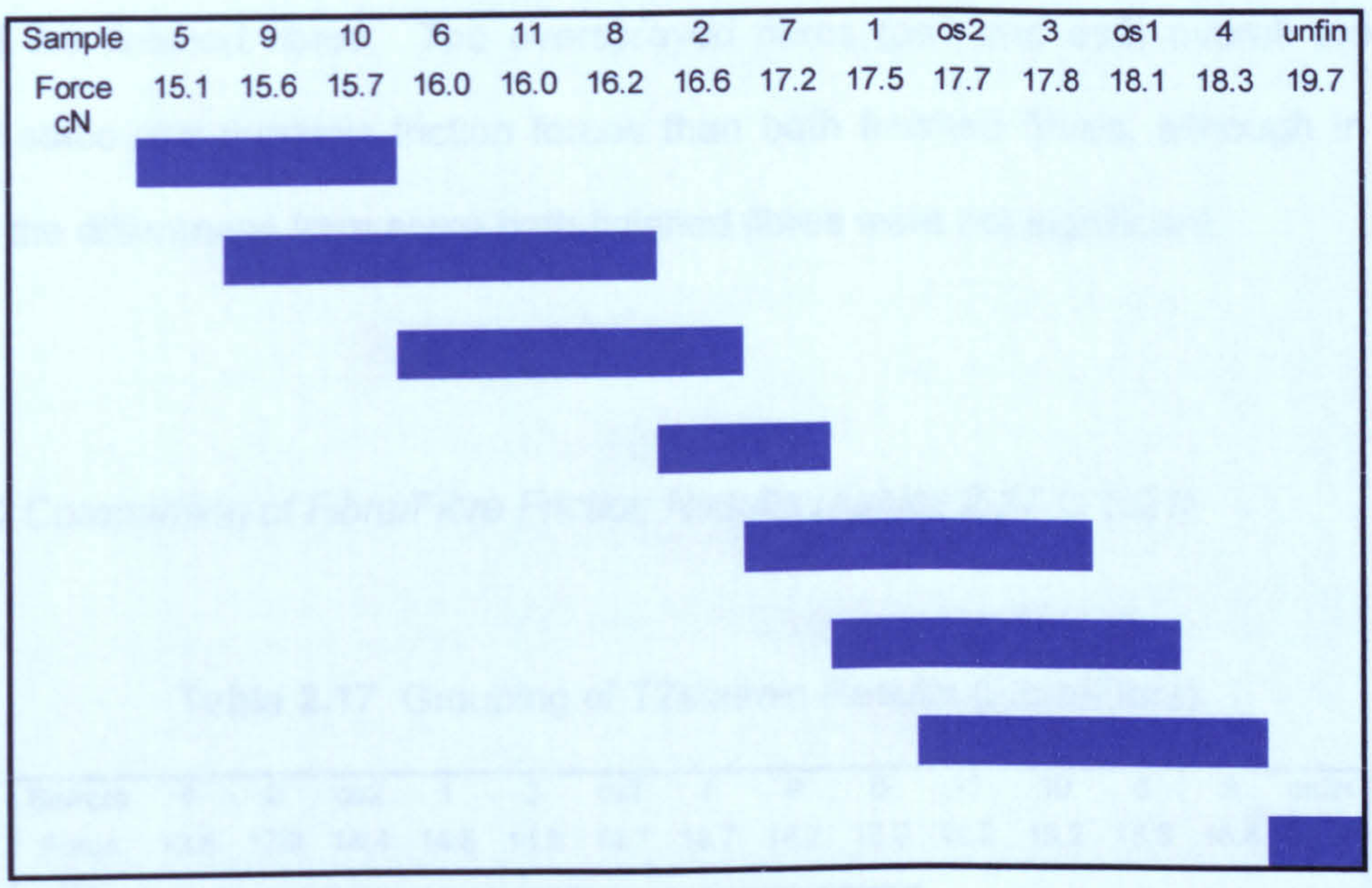
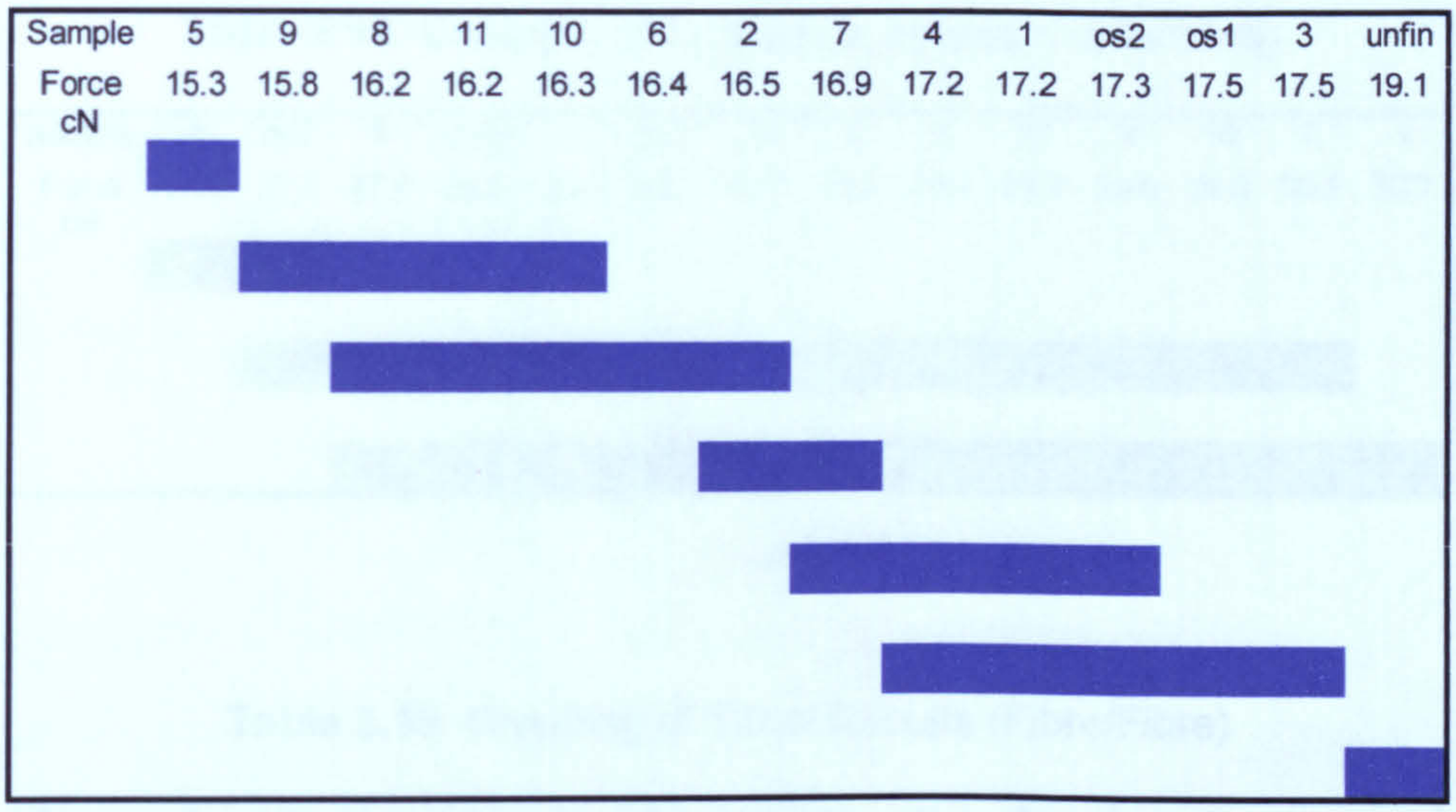


Table 2.16 Grouping of T2dyn5 Results (Fibre/Metal)

Sample	5	9	8	11	10	6	2	7	4	1	os2	os1	3	unfin
Force cN	15.3	15.8	16.2	16.2	16.3	16.4	16.5	16.9	17.2	17.2	17.3	17.5	17.5	19.1



It is clear that, whilst there is some grouping and overlap of results, unfinished fibres produced significantly higher static and dynamic friction forces (95% confidence) than any of the finished fibres. The oversprayed fibres (os1 and os2) overall produced higher static and dynamic friction forces than bath finished fibres, although in some cases the differences from some bath finished fibres were not significant.

2.2.3.2 Comparison of Fibre/Fibre Friction Results (Tables 2.17 to 2.21)

Table 2.17 Grouping of T2statmin Results (Fibre/Fibre)

Sample	4	2	os2	1	3	os1	7	9	6	11	10	8	5	unfin
Force cN	13.5	13.9	14.4	14.5	14.6	14.7	14.7	14.7	15.0	15.2	15.2	15.3	15.4	16.4

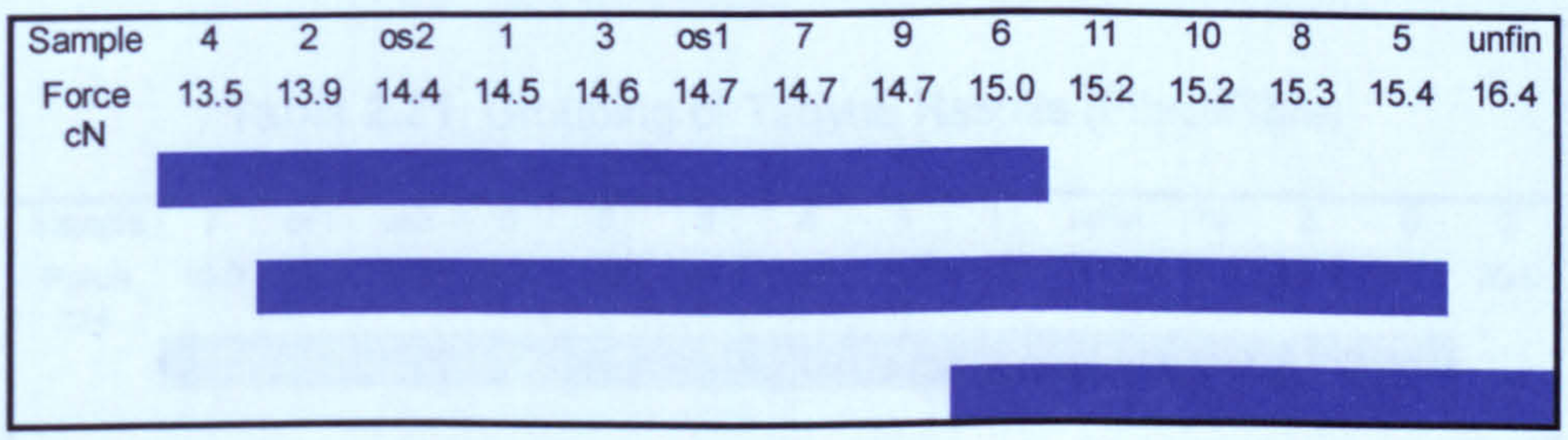


Table 2.18 Grouping of T2statmax Results (Fibre/Fibre)

Sample	8	os2	2	unfin	7	os1	4	3	5	11	9	10	6	1
Force cN	24.6	27.1	27.8	28.5	28.5	28.7	28.7	29.2	29.4	29.4	29.6	29.6	30.1	30.7

Table 2.19 Grouping of T2del Results (Fibre/Fibre)

Sample	8	unfin	os2	7	2	5	os1	11	10	3	9	6	4	1
Force cN	9.2	12.1	12.7	13.8	13.8	13.9	14.0	14.3	14.4	14.6	14.9	15.1	15.3	16.1

Table 2.20 Grouping of T2dyn0 Results (Fibre/Fibre)

Sample	os2	7	os1	4	5	1	9	unfin	3	10	6	8	11	2
Force cN	15.8	16.0	16.1	16.5	16.6	16.7	16.8	17.2	17.2	17.2	17.3	17.3	17.4	18.5

Table 2.21 Grouping of T2dyn5 Results (Fibre/Fibre)

Sample	7	os1	os2	5	6	9	4	1	11	unfin	10	3	8	2
Force cN	16.0	16.1	16.2	16.5	16.6	16.6	16.6	16.8	17.0	17.2	17.6	17.7	18.0	20.9

Although sample 8 (20% 092: 80% P2DL, 50 gl^{-1} emulsion, dipped at 80°C for 60 seconds) and the unfinished fibres produced the lowest 'scroop', shown by the low values of T2del (Table 2.19), and sample 2 (20% 092: 80% P2DL, 50 gl^{-1} emulsion, dipped at 21°C for 1 second) produced high dynamic friction (Table 2.21), no overall trends in fibre/fibre friction behaviour were apparent.

2.2.3.3 Comparison of Results From Each Application Method

The average (avg) friction forces from the bath finished fibres were compared to those of the oversprayed and unfinished fibres. Figures 2.21 to 2.25 and 2.26 to 2.30 illustrate fibre/metal and fibre/fibre results respectively. Error bars represent 95% confidence intervals.

Fibre/Metal Friction

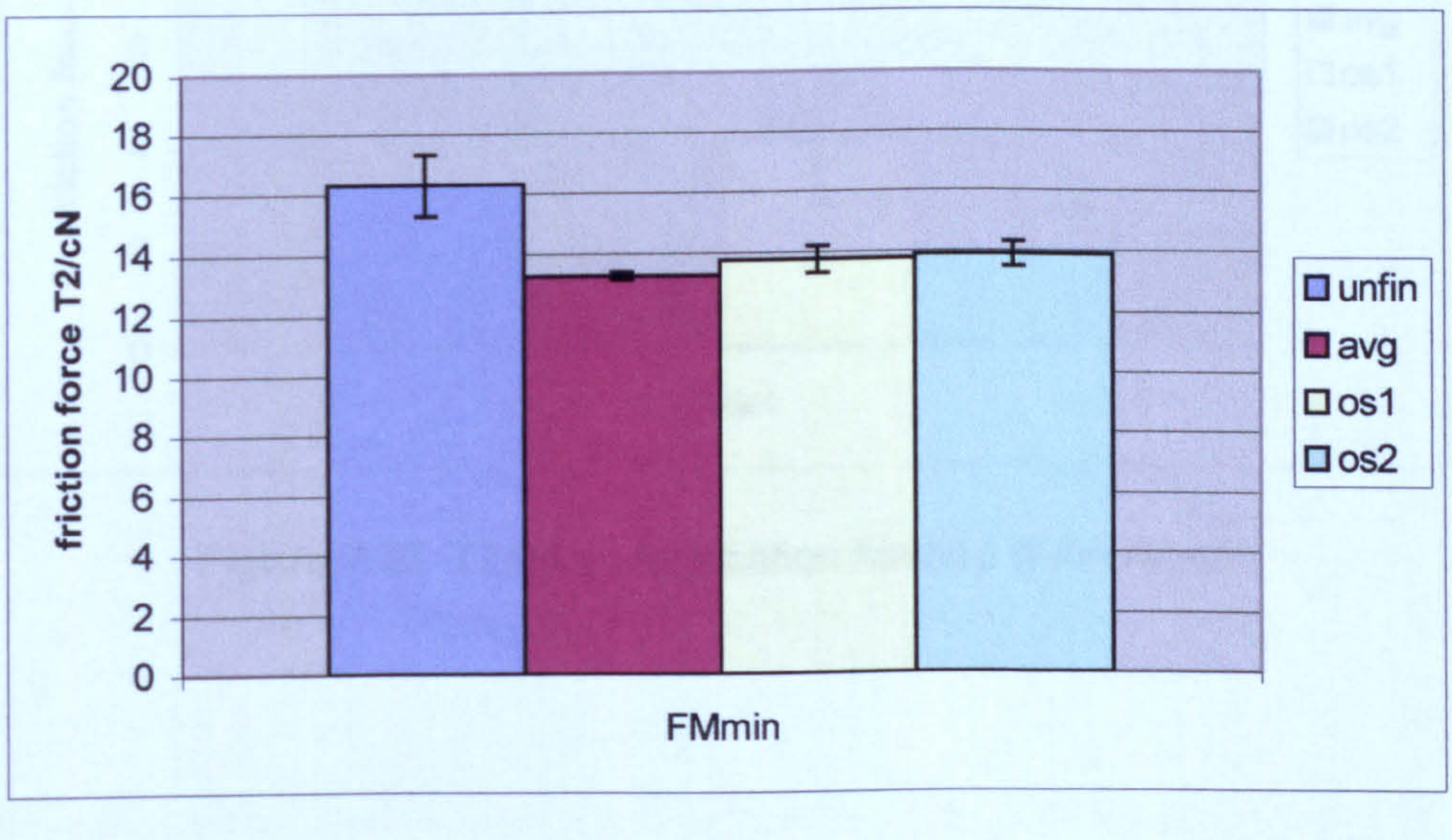


Figure 2.21 T2statmin vs Application Method (Fibre/Metal)

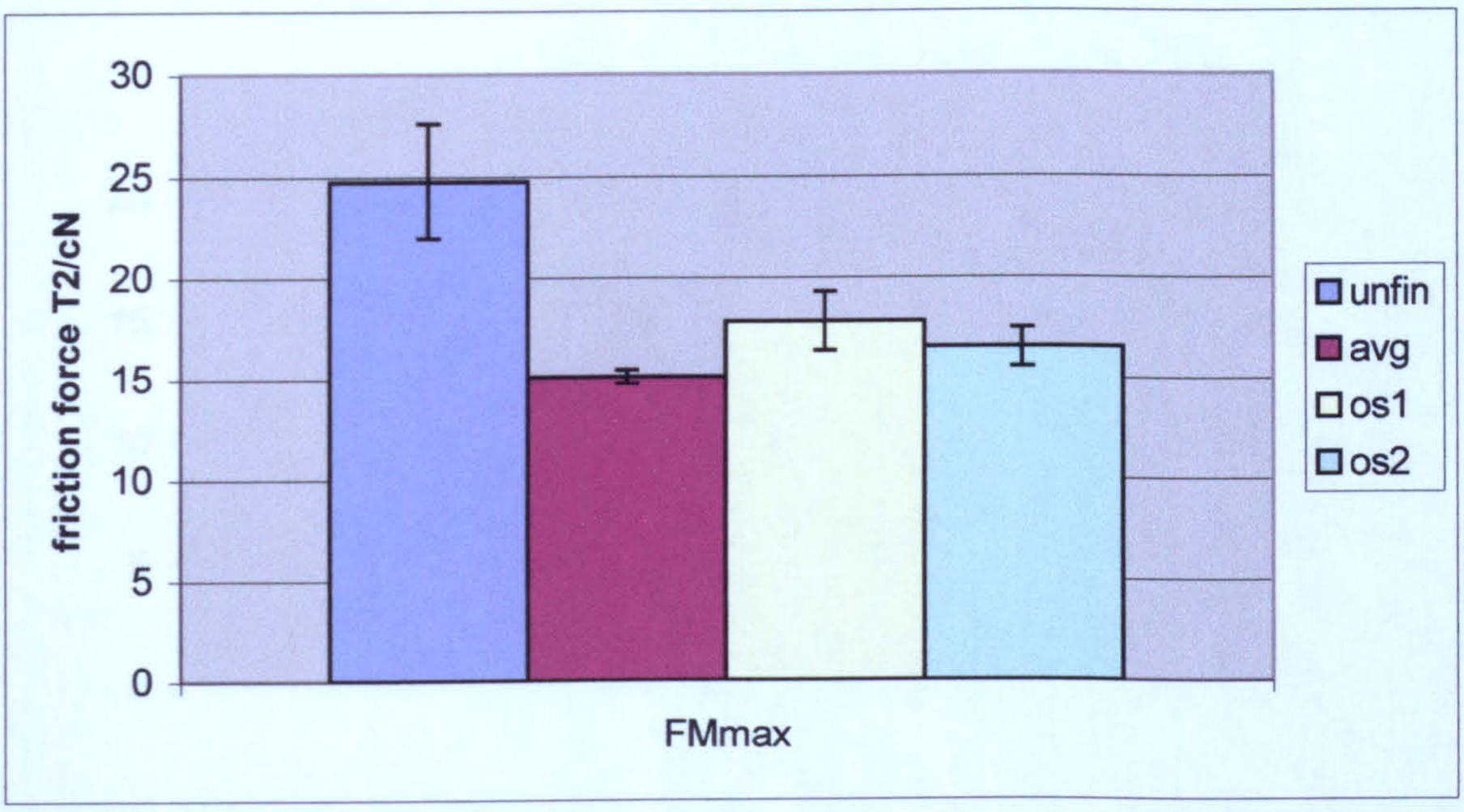


Figure 2.22 T2statmax vs Application Method (Fibre/Metal)

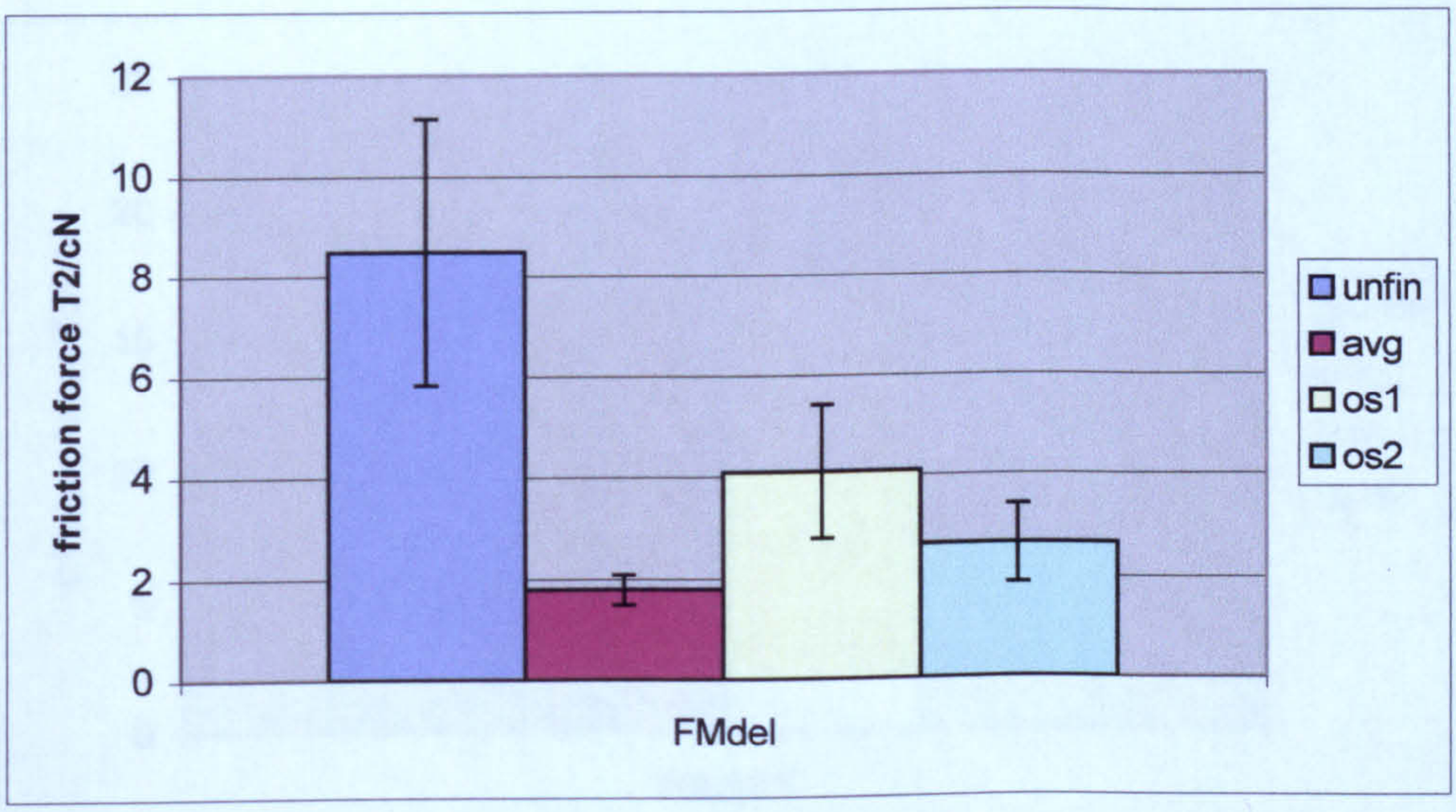


Figure 2.23 T2del vs Application Method (Fibre/Metal)

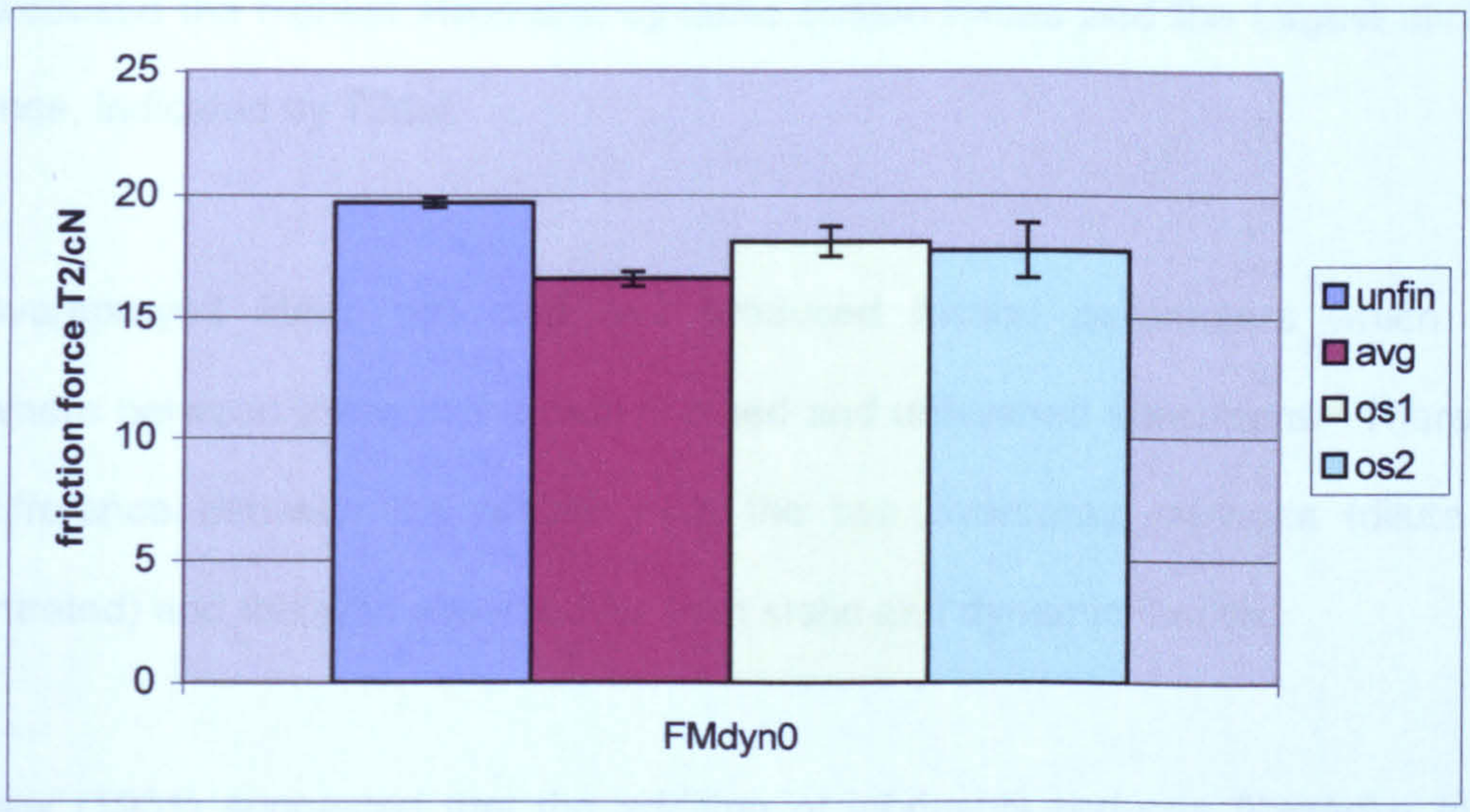


Figure 2.24 T2dyn0 vs Application Method (Fibre/Metal)

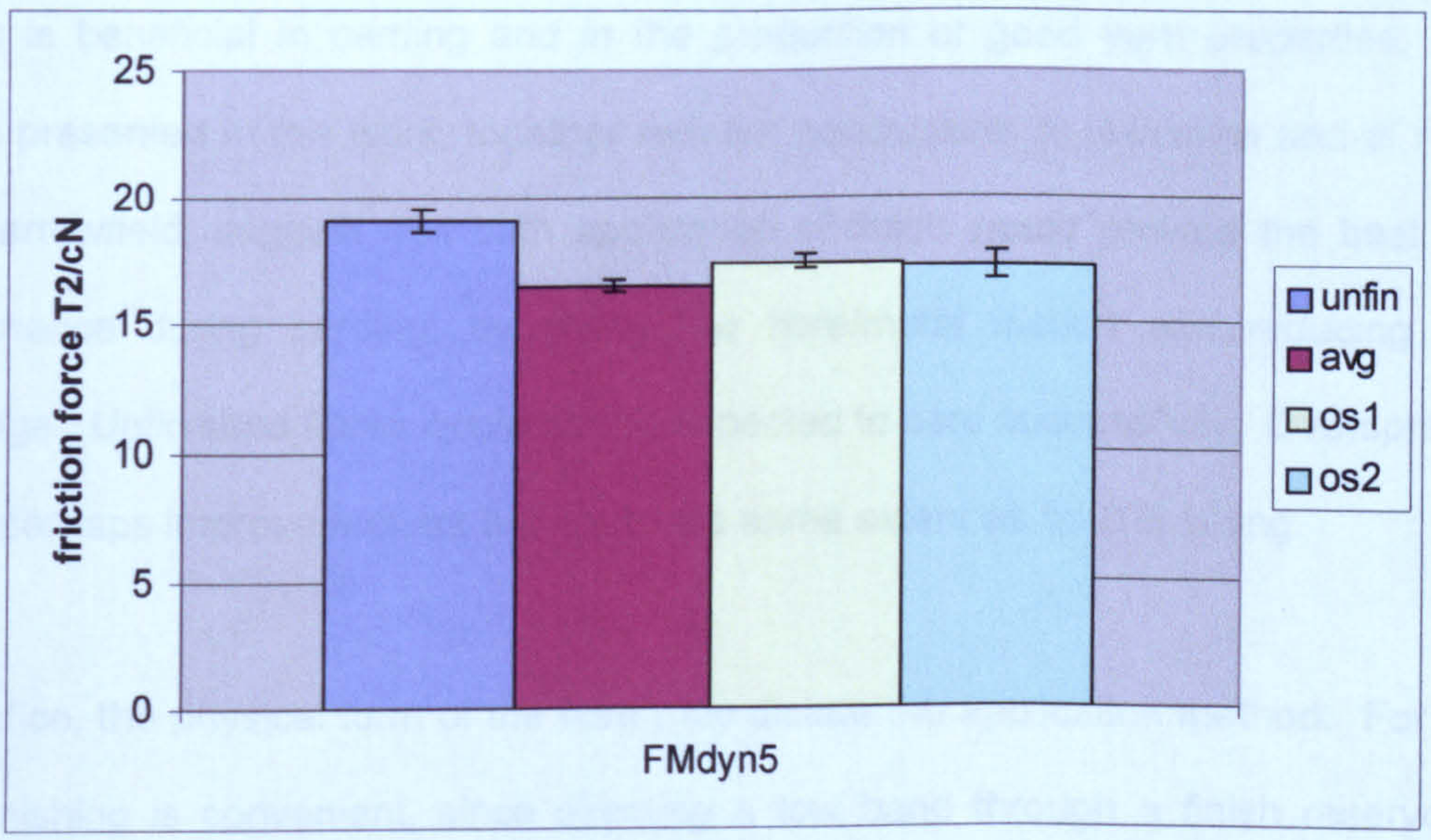


Figure 2.25 T2dyn5 vs Application Method (Fibre/Metal)

Figures 2.21 to 2.25 demonstrate that overall, bath application produced the lowest static friction and dynamic fibre/metal friction forces (T2statmin, T2statmax, T2dyn0 and T2dyn5). The smallest difference between minimum and maximum friction forces, due to stick-slip behaviour (i.e. T2del) was also produced by bath finishing. Unfinished

fibre produced the highest static and dynamic friction forces and the largest stick-slip difference, indicated by T2del.

The oversprayed fibres os1 and os2 produced friction parameters which were somewhere between those of the bath finished and unfinished specimens. There was little difference between the results from the two overspray methods (dilute and concentrated) and this was observed for both static and dynamic friction.

Henshaw (1961) suggested that the addition of lubricants reduces fibre/wire friction which decreases fibre breakage during carding. Haigh and Harrowfield (1990) observed that most fibre breakage occurs during carding and that fibres with low fibre/metal friction gave the lowest occurrence of breakage. Hence, low fibre/metal friction is beneficial in carding and in the production of good yarn properties. The results presented in this work, together with the conclusions of Henshaw and of Haigh and Harrowfield, suggest that bath application of finish would provide the best fibre performance during carding, by giving low fibre/metal friction and reducing fibre breakage. Unfinished fibres would not be expected to card successfully. Overspraying would perhaps improve matters but not to the same extent as bath finishing.

In practice, the physical form of the fibre may dictate the application method. For tow, bath finishing is convenient, since directing a tow band through a finish reservoir is relatively simple. For staple fibres, however, the finish is often applied to a moving pile or mat of fibres on a conveyor. Guiding the conveyor through a bath is not feasible because the pile of short (typically 38mm), individual fibres would not remain intact, making drying and further processing into bales of fibres impossible. Here, overspraying or dripping finish from a trough onto the pile of staple fibres is the most

convenient option (Szokalo, 1994), even though the resulting distribution of finish is not ideal.

Fibre/Fibre Friction

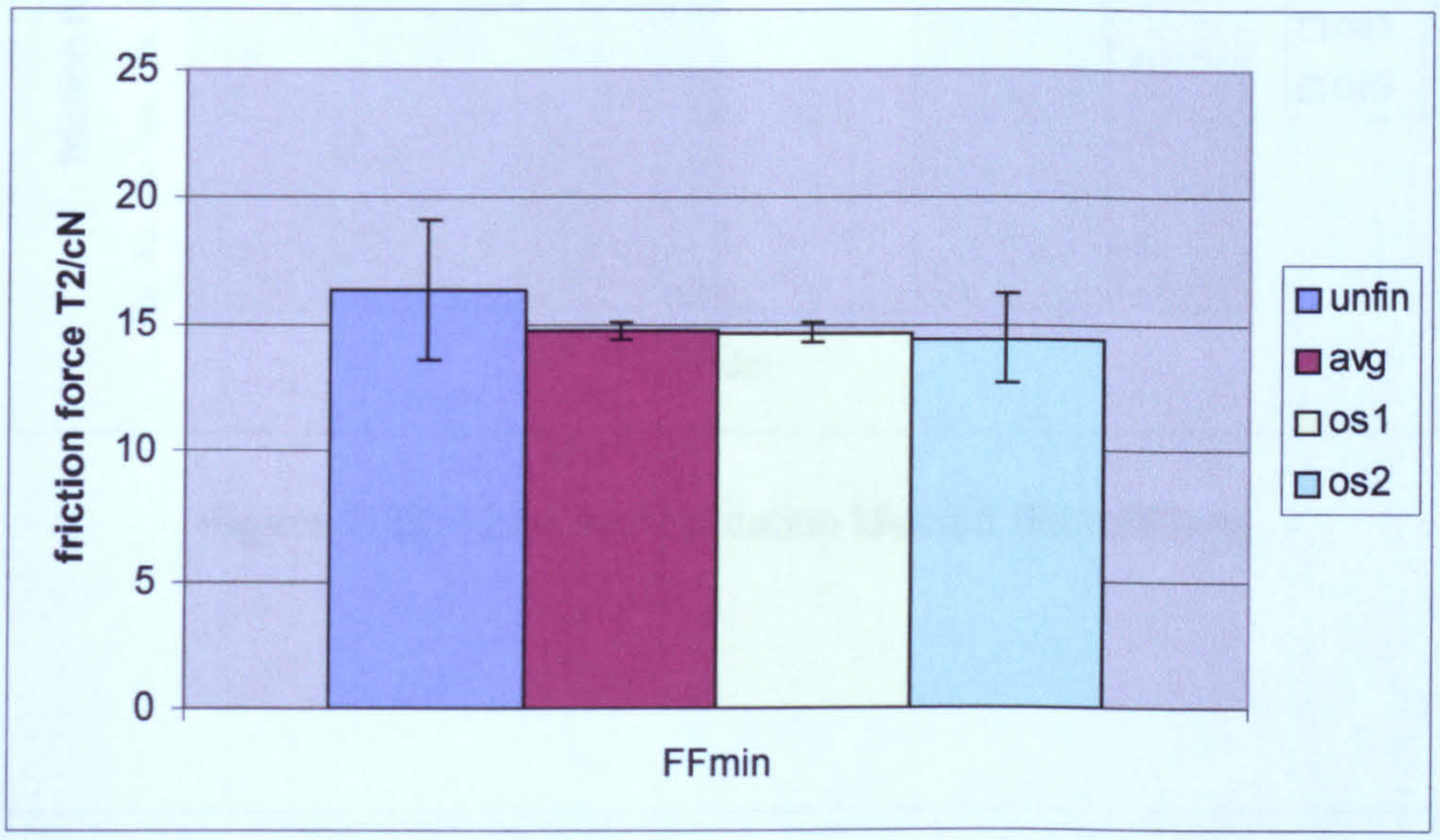


Figure 2.26 T2statmin vs Application Method (Fibre/Fibre)

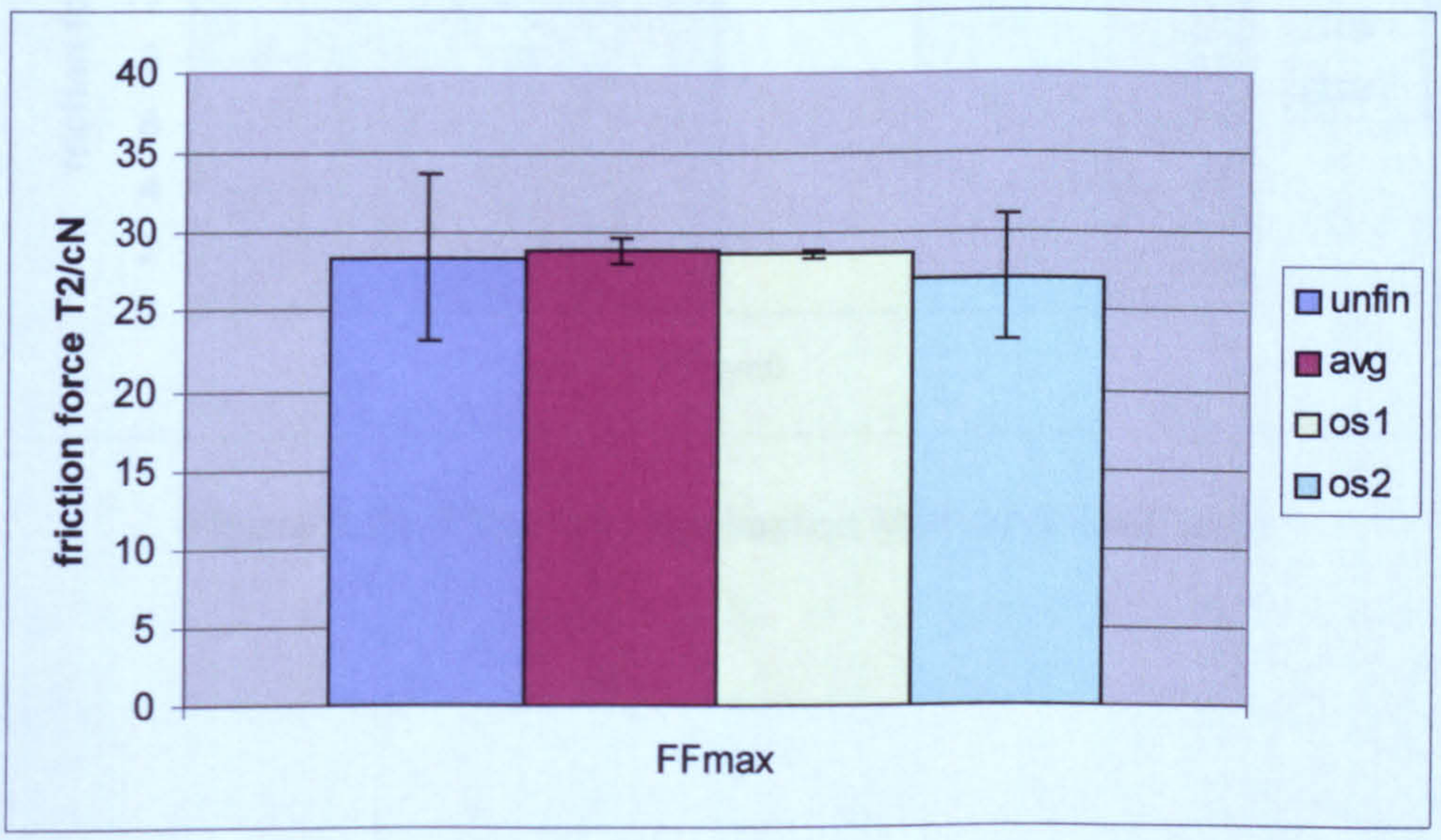


Figure 2.27 T2statmax vs Application Method (Fibre/Fibre)

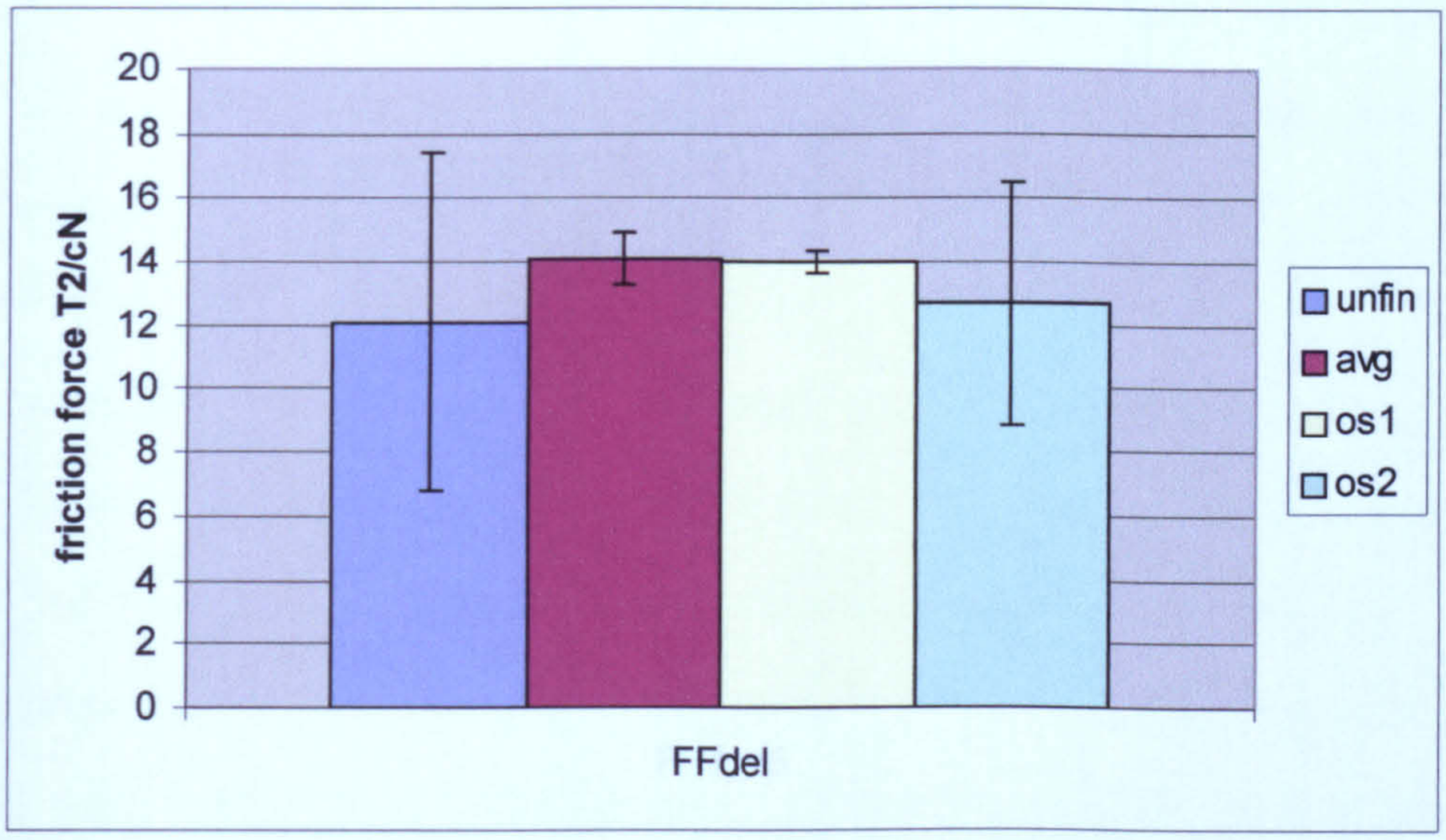


Figure 2.28 T2del vs Application Method (Fibre/Fibre)

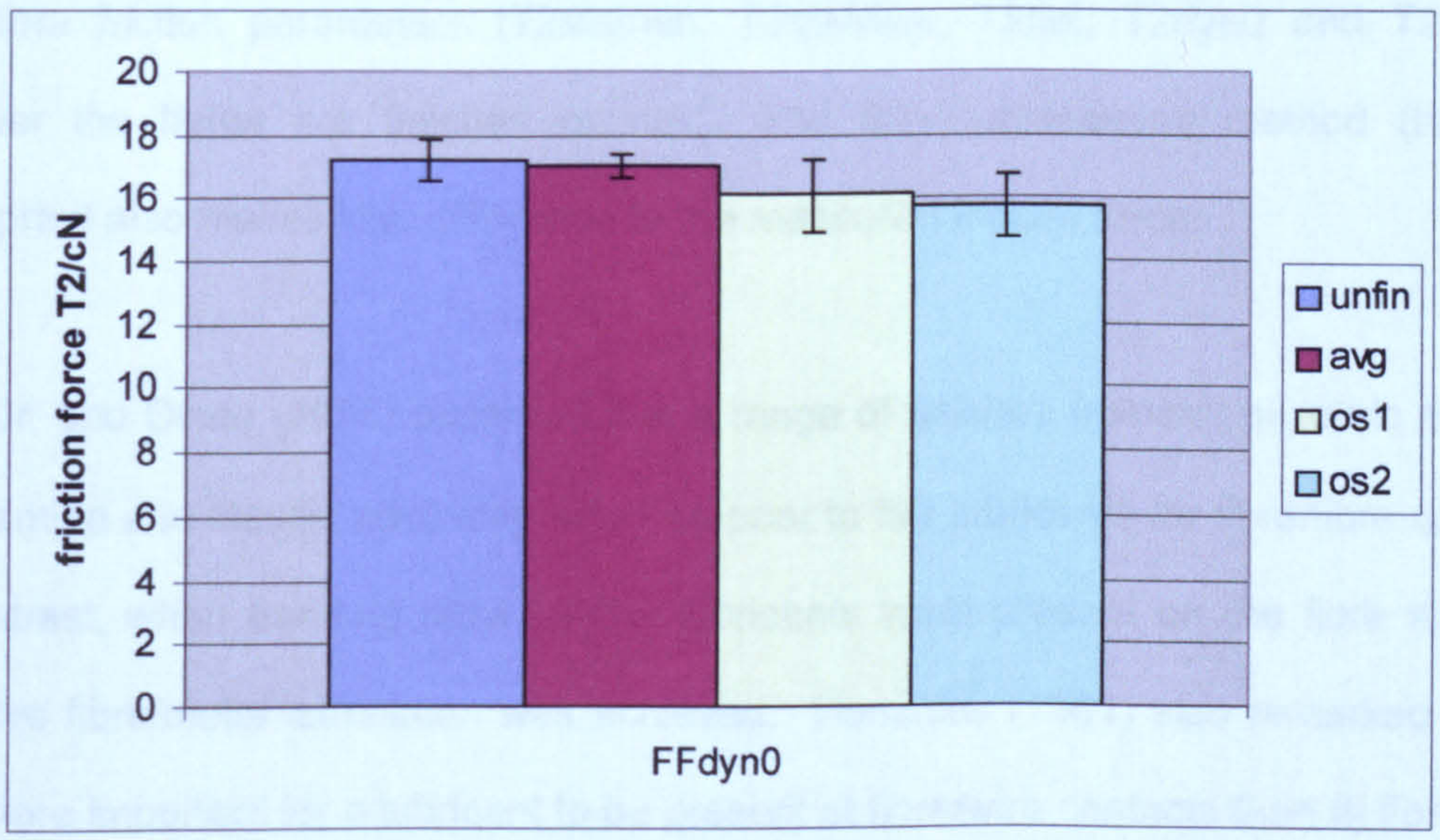


Figure 2.29 T2dyn0 vs Application Method (Fibre/Fibre)

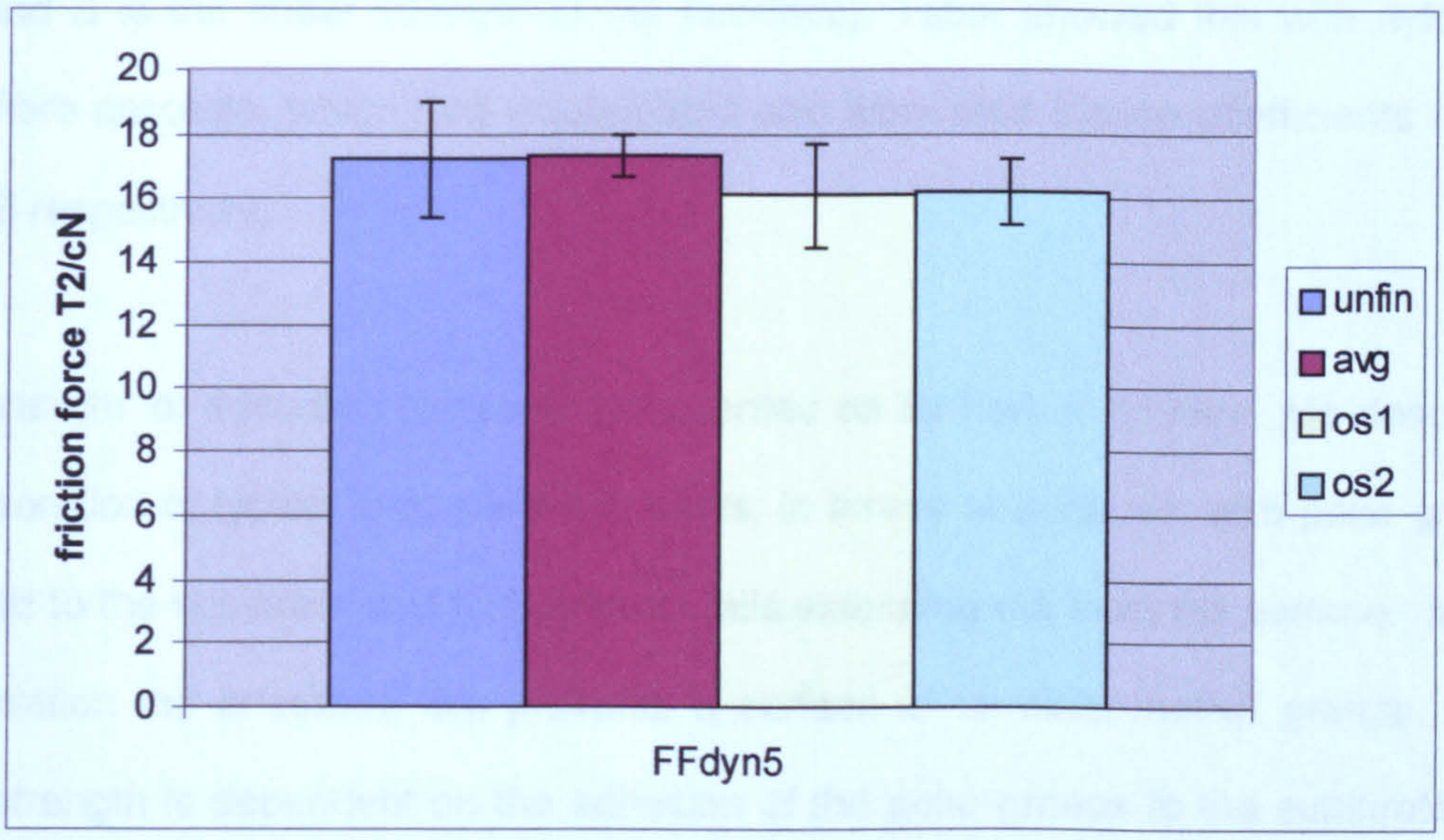


Figure 2.30 T2dyn5 vs Application Method (Fibre/Fibre)

Figures 2.26 to 2.30 demonstrate that there is little difference between any of the fibre/fibre friction parameters (T2statmin, T2statmax, T2del, T2dyn0 and T2dyn5), whether the fibres are finished or not. The finish application method (bath or overspray) also makes little difference to the measured friction forces.

Fort, Jr. and Olsen (1961) observed that a range of finishes (mineral oil, oleic acid, n-octyl amine and stearic acid) only acted as poor to fair lubricants for fibre/fibre contact. In contrast, when bonding sites for the lubricants were present on the fibre surface, effective fibre/metal lubrication was achieved. Henshaw (1961) also remarked that it was more important for a lubricant to be present at fibre/wire contacts than at fibre/fibre contacts since the lubricant does not have a great effect on fibre/fibre friction. Tabor (1960) concluded that some lubricants do not affect the boundary friction of polymers significantly, since the shear strength of the lubricant cannot differ greatly from that of the polymer. The shear strength of the asperities in contact at the sliding junction determines the friction force (F=AS, where F is the friction force, A is the true contact

area and S is the shear strength of the interface). Tabor showed this with nylon on nylon fibre contacts, which had unlubricated and lubricated friction coefficients of 0.8 and 0.6 respectively.

The 'strength' of adsorbed films was commented on by Fort Jr. (1962). He described the adsorption of typical long chain lubricants, in arrays at surfaces, with polar groups attached to the substrate and hydrocarbon tails extending out from the surface. In this configuration the adsorbed film presents a surface of terminal methyl groups. The shear strength is dependent on the adhesion of the polar groups to the substrate and the cohesion between adsorbed molecules in the film. Liquid lubricants were said to be less effective at reducing friction because they adsorb less, and the attraction between polar groups and the substrate is weak. When intermolecular cohesion increases to the point at which the lubricants are solid, friction is reduced to the same level (μ~0.1), regardless of the lubricant chemistry. Again the conclusion is that the shear strength of different types solid lubricants is about the same. Fort Jr. demonstrated the difference between a solid and liquid lubricant by examining wear scars on PET covered with stearic acid. There was a large increase in damage associated with a dramatic increase in friction when the lubricant melted (m.p. 67-69°C).

It can be concluded from this work and from previous studies reported in the literature that lubricating fibres with some finish types may have little effect on fibre/fibre friction, whatever application method is used. Once again, the compounds used as fibre finishes, and discussed here, are distinguished from fabric softener type molecules which are known to reduce inter-fibre friction (Clint, 1990, Sebastian *et al.*, 1986). In contrast, the presence of finishes can have a significant effect in reducing fibre/metal

friction and the method of finish application also has an influence on the fibre/metal friction forces.

Table 2.22 compares fibre/metal and fibre/fibre friction forces, averaged over all of the results from this study (see Tables 2.5, 2.6, 2.10 and 2.11 for original data).

Table 2.22 Comparison of Average Fibre/Metal and Fibre/Fibre Friction Forces (cN) with Standard Deviations

	T2statmin	T2statmax	T2del	T2dyn0	T2dyn5
Fibre/Metal	13.6±0.9	16.1±2.8	2.5±2.1	17.0±1.3	16.8±1.0
Fibre/Fibre	14.8±1.0	28.7±2.1	13.9±2.2	16.9±1.1	17.1±1.6

Static fibre/fibre friction was higher than static fibre/metal friction (T2statmin and T2statmax). El Mogahzy and Broughton (1993) also observed that fibre/fibre contacts produced higher friction than fibres sliding against metal when they pulled apart fringes of cotton fibres. Here, the stick-slip effect, indicated by T2del was greater for fibre/fibre contacts than for fibre/metal contacts.

There was little difference between fibre/fibre and fibre/metal dynamic friction. Billica (1977) suggested that it is unnecessary to treat yarn/guide and yarn/yarn contacts separately under hydrodynamic sliding. This is because the properties of the finish dominate when the two sliding surfaces are separated at high speed, by a continuous finish layer, although as Schick (1973d) points out, good wetting of the fibres by the finish is necessary. If good wetting occurs, dynamic friction generally decreases as the finish viscosity is reduced.

2.2.4 Friction vs Normal Load

Amontons' law states that friction between sliding bodies is proportional to the normal load and that the ratio of friction/load is constant. In section 1.3.2 it was proposed that this relationship does not describe friction of textiles. A better description of textile friction is provided by the equation

$$F = aR^n.$$

The coefficients, a and n, can be deduced by plotting ln(F) against ln(R), where F is the measured friction force and R is the normal load.

Previous work concentrated on the friction vs load relationship for fibre/fibre contacts. In these studies, some departure from Amontons' law was observed, i.e. the index, n, was not found to be unity. A summary of the literature values of n is given in Table 2.23.

Table 2.23 Literature Values of the Index n for Fibre/Fibre Contacts

Worker(s)	Fibre type	Value of index n
Guthrie and Oliver (1952)	Viscose rayon 1.5 denier	Static: 1.02 (finished) 0.89 (extracted) Kinetic: 0.94 (finished) 0.98 (extracted)
Howell and Mazur (1953)	Viscose rayon	0.91
Lord (1955)	Cotton	0.886
Mazur (1955)	Cleaned viscose	0.908
Viswanathan (1966)	Viscose	0.64 – 0.75
El Mogahzy and Broughton (1993)	Cotton	0.641 and 0.675 depending on fibre source

Unless stated in Table 2.23, it was unclear from the literature whether or not the fibres used in the determination of the index, n, were finished or unfinished. Mazur's fibres were cleaned in petroleum ether, alcohol and distilled water. Guthrie and Oliver presented static and kinetic values of the index, n, for both finished and extracted (i.e. unfinished) fibres. Guthrie and Oliver's results demonstrated that the presence of finish increased the static friction index and reduced the dynamic friction index, although the static friction behaviour of the finished fibres was close to obeying Amontons' law (i.e. when n=1). The kinetic index of the extracted fibres was also close to unity, suggesting that the dynamic friction coefficient has little dependence on load.

Guthrie and Oliver also produced n values for 3 denier, 4.5 denier and 8 denier viscose fibres, however the results were somewhat different to those of 1.5 denier viscose. Only 1.5 denier (~1.7 decitex) values of n, from Guthrie and Oliver, are included in the Table 2.23, since these will be most relevant for comparison with the present work, in which 1.7 decitex viscose was used.

Viswanathan and El Mogahzy and Broughton's results suggested that fibre/fibre friction behaviour was closer to being elastic rather than plastic (n=2/3 for ideal elastic behaviour, n=1 for plastic behaviour). Overall, there is some disagreement as to whether the nature of viscose and cotton, fibre/fibre friction, is elastic or plastic, as shown by the different values of n for the same fibres (see table 2.23).

In this present work, the friction vs load relationship for finished fibre/metal contact was investigated. R was varied by changing the tension weight T1. 10g, 30g and 50g weights were used and T2 was measured between finished fibres and the metal pin (see section 2.1.1 for method). Finished fibres 9,10 and 11 (see section 2.1.1 for details) were used to produce three results at each of the three loads. For the 10g

weight, results are given as the averages over the five replicates, shown earlier in Table 2.5. The friction vs load data are displayed in Table 2.24. The loads are calculated by multiplying the weight by the gravitational constant g (9.81 ms^{-2}). The load includes the weight of the fibre hanging over the pin (0.025g), the weight of a clip (0.342g) and the tension weight.

Table 2.24 Friction vs Load Data

Load/cN	T2statmin	T2statmax	T2dyn0	T2dyn5
10.17	13.4	15.3	16	16.2
10.17	13.4	14.8	15.7	16.3
10.17	12.8	14.9	15.6	15.8
29.79	40.3	41.3	48.3	47
29.79	38.1	39.5	49.2	48.8
29.79	37	37.4	47.8	47.2
49.41	61.5	64	80.5	81.5
49.41	61.5	68.1	80	76.5
49.41	65.5	73.1	80	79

The values of a and n are obtained from the gradients and intercepts of plots of ln(T2) vs ln(load) shown in Figures 2.31 to 2.34.

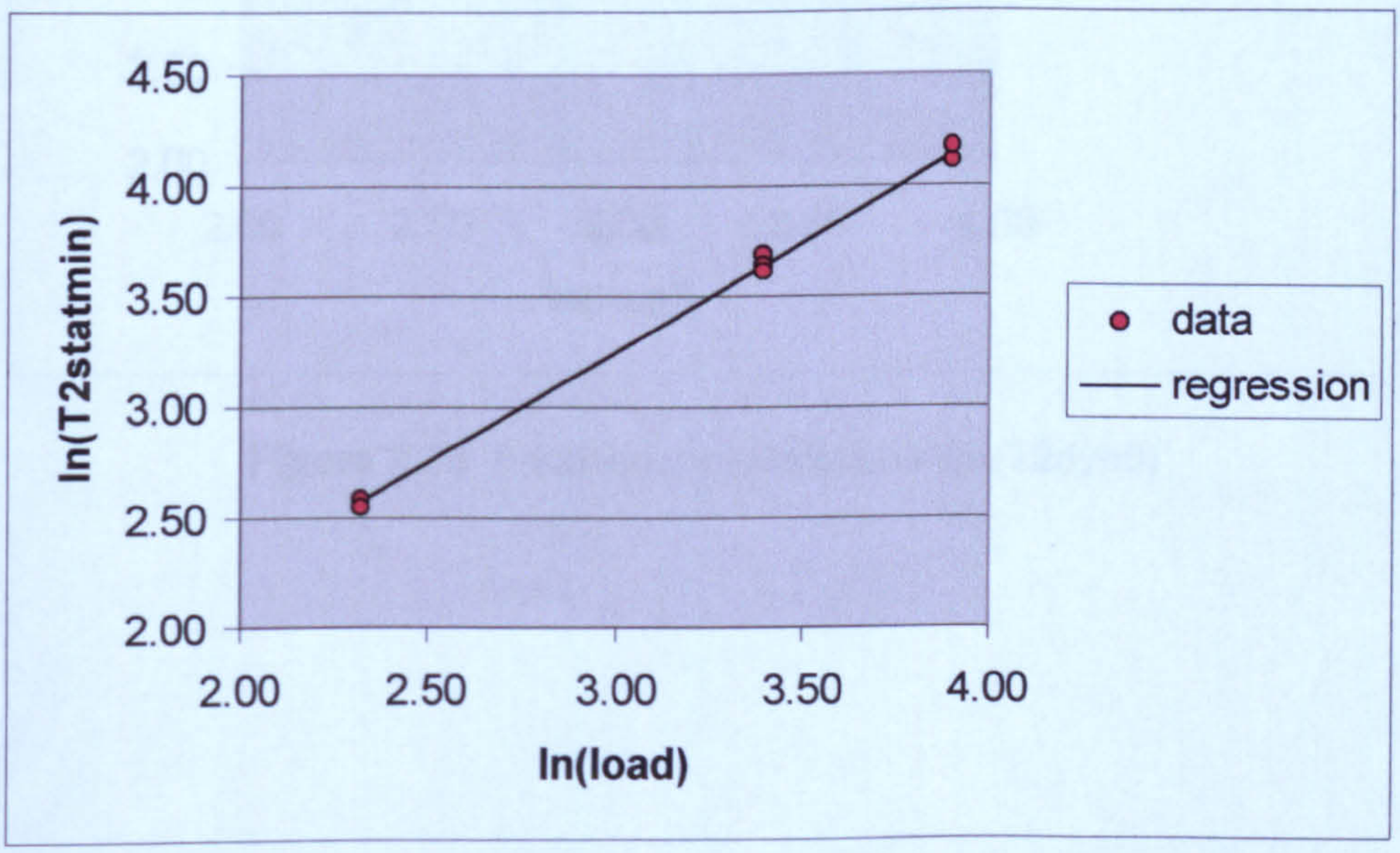


Figure 2.31 Friction/Load Relationship (T2statmin)

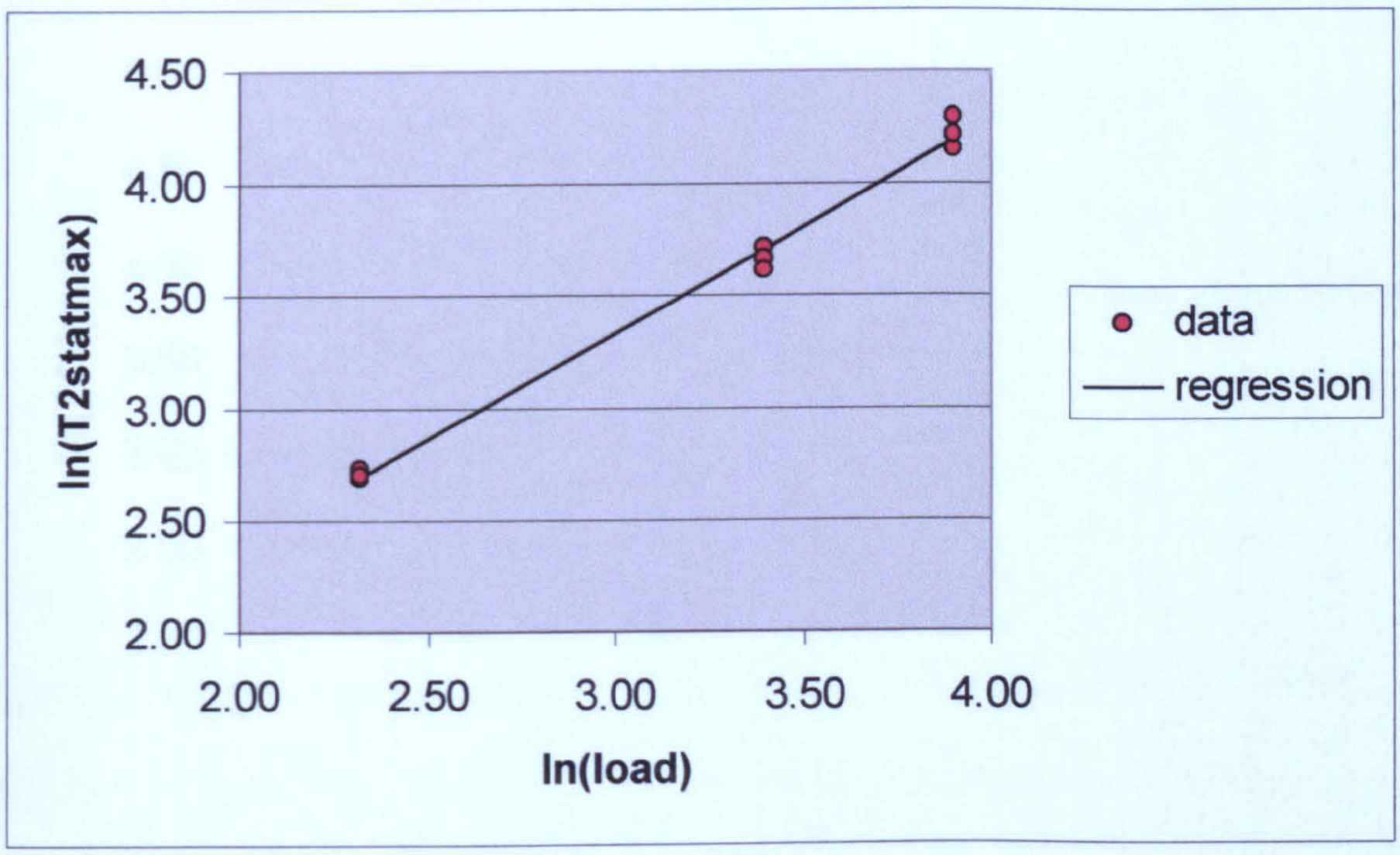


Figure 2.32 Friction/Load Relationship (T2statmax)

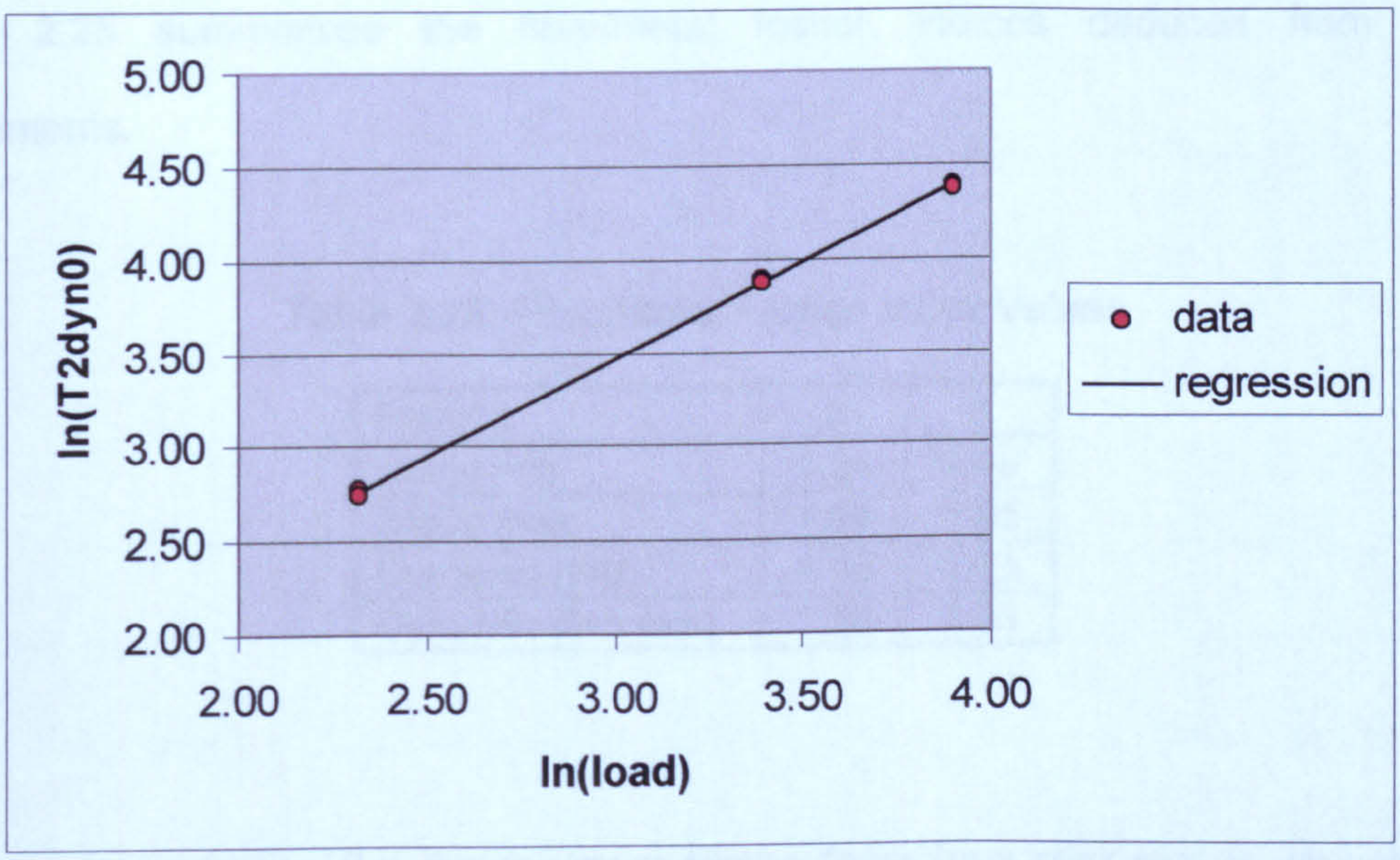


Figure 2.33 Friction/Load Relationship (T2dyn0)

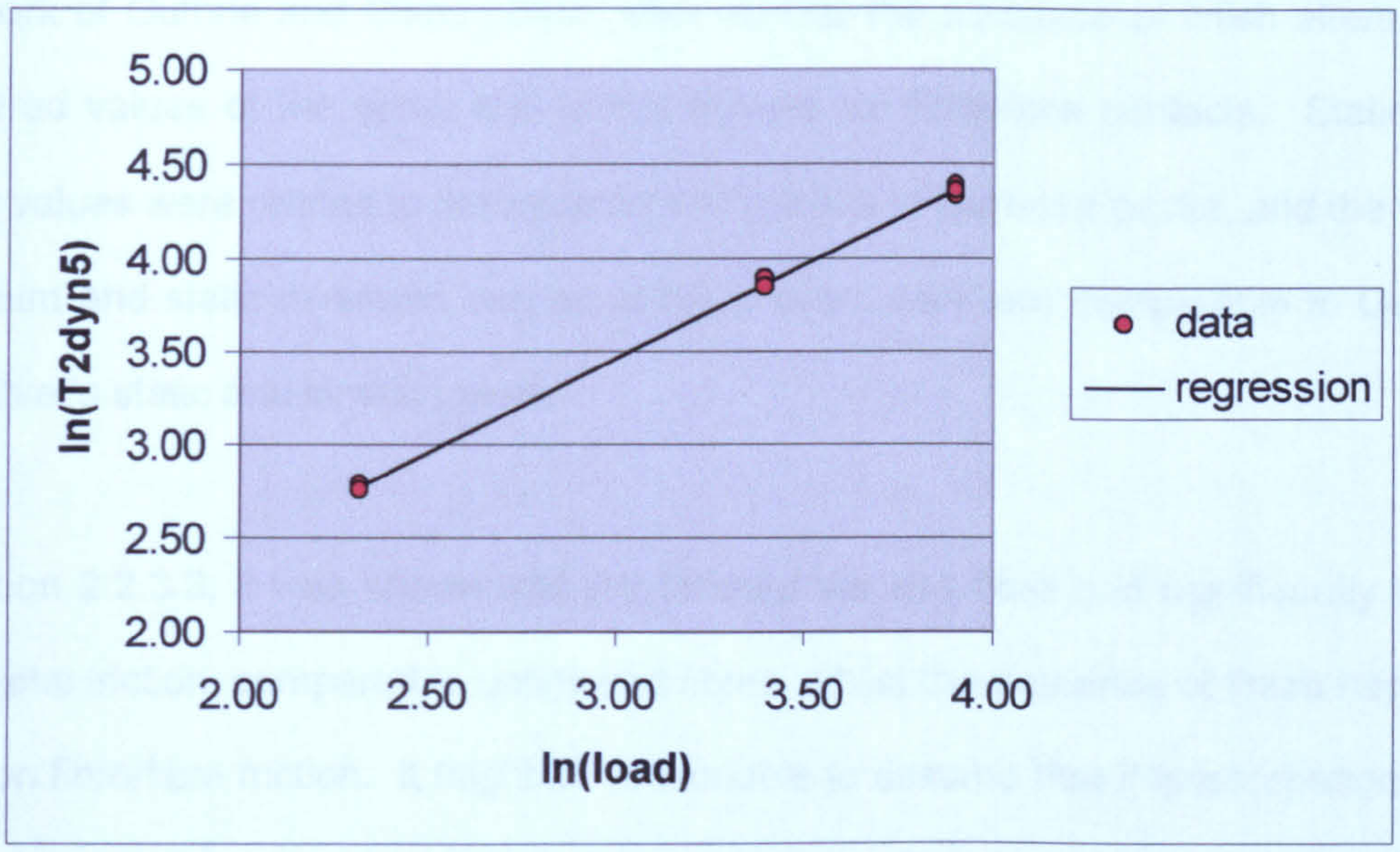


Figure 2.34 Friction/Load Relationship (T2dyn5)

Table 2.25 summarises the fibre/metal friction indices deduced from these experiments.

Table 2.25 Fibre/Metal Friction Index Values

Friction	a	n
Static min	1.34	0.99
Static max	1.64	0.95
Dynamic (t=0)	1.45	1.03
Dynamic (t=5 min)	1.56	1.01

Static minimum friction (i.e. the minimum friction force from stick-slip) is very close to obeying Amontons' law (n=0.99). The static friction maximum values showed a small departure from ideal plastic behaviour, in which n would be unity. For ideal elastic behaviour n=2/3.

The work of Guthrie and Oliver (1952) showed that the presence of finish altered the measured values of the static and kinetic indices for fibre/fibre contacts. Static and kinetic values were related to the maxima and minima of stick-slip peaks, and the static maximum and static minimum indices of the present work are comparable to Guthrie and Oliver's static and kinetic values.

In section 2.2.3.3, it was shown that the finished viscose fibre had significantly lower fibre/metal friction, compared to unfinished fibres, whilst the presence of finish had little effect on fibre/fibre friction. It might be reasonable to assume that if finish changes the friction index, n, for fibre/fibre contacts (as show by Guthrie and Oliver), then finish would have an effect on n, for fibre/metal contacts. The magnitude and direction of the change in the value of n is not known, since in the present study, only lubricated fibres were used. The measurement of the index, n, for unfinished fibres would be of interest, but unfinished fibres would not usually be processed into yarns, so a knowledge of the friction vs load relationship for unfinished fibre/metal contacts may have little practical significance.

In the dynamic experiments n~1, suggesting that the high speed fibre/metal friction coefficient was independent of the load applied. This does not follow the trends suggested by Olsen (1969) and Schick (1973a) for lubricated yarns, where an increase in load resulted in a decrease in friction (see section 1.3.2, Figure 1.2 and section 1.3.4, Figure 1.4). A possible explanation for this discrepancy is that the friction measured in these experiments was within the plateau region of the friction coefficient vs (speed x viscosity/load) curves presented by Olsen and Schick. In this region a change in load would make little difference to the magnitude of the dynamic friction coefficient. The findings of the present study are in agreement with those of Nikonova *et al.* (1971), who observed that there was a negligible influence on the friction

coefficient of capron yarn against a contact roller (determined from capstan experiments) when the tensioning load was varied between 5g and 30g, at speeds between 0 and 30m min^{-1}.

Previous literature studies of fibre/fibre contact showed departures from Amontons' law, although there was some disagreement as to whether the friction behaviour was mainly plastic or elastic in nature. The presence of finish was shown to affect the friction vs load relationship (Guthrie and Oliver, 1952). In the present work, the friction vs load relationship of lubricated fibre/metal contact was studied. Sliding was mainly plastic in behaviour at low speed, since the index n was close to unity. Also, under these experimental conditions, the dynamic friction coefficient was largely independent of applied load.

2.2.5 Friction Coefficients

2.2.5.1 Measured Friction Coefficients

Using the capstan equation ($T_2/T_1=e^{\mu\theta}$) and the data of Tables 2.5, 2.6, 2.10 and 2.11, friction coefficients were calculated. T_1 was 10.17cN (10g weight, 0.34g clip and 0.025g of fibre) and the wrap angle $\theta=90°$. Fibre/metal and fibre/fibre coefficients are given in Tables 2.26 and 2.27. The coefficients are calculated from the average values of T_2 over 5 results (fibre/metal) and 3 results (fibre/fibre). The 'statdel' values given are the differences between static maximum and static minimum (statmax – statmin) coefficients, and as with the raw data (i.e. T2 force values), the difference indicates the magnitude of stick-slip behaviour.

Friction coefficient vs finish application method is shown in Figures 2.35 and 2.36. For the bath finished fibres the coefficient for each parameter (i.e. statmin, statmax, statdel,

dyn0 and dyn5) was calculated as an average of the results numbered one to eleven in Tables 2.26 and 2.27. The significance of the differences in friction between the application method has already been discussed in section 2.2.2.3. Tables 2.26 and 2.27 and Figures 2.35 and 2.36 permit comparison of the friction coefficients found in this work with those reported in the literature.

Table 2.26 Fibre/Metal Friction Coefficients

Sample	T2statmin	T2statmax	T2statdel	T2dyn0	T2dyn5
Unfinished	0.30	0.57	0.27	0.42	0.40
1	0.19	0.28	0.09	0.34	0.34
2	0.16	0.18	0.02	0.31	0.31
3	0.19	0.29	0.10	0.36	0.35
4	0.16	0.34	0.18	0.37	0.33
5	0.17	0.23	0.06	0.25	0.26
6	0.17	0.19	0.02	0.29	0.30
7	0.19	0.26	0.07	0.33	0.32
8	0.14	0.22	0.08	0.30	0.30
9	0.15	0.24	0.10	0.27	0.28
10	0.18	0.24	0.06	0.28	0.30
11	0.17	0.26	0.08	0.29	0.30
os1	0.19	0.36	0.17	0.37	0.34
os2	0.20	0.31	0.11	0.35	0.34

Table 2.27 Fibre/Fibre Friction Coefficients

Sample	T2statmin	T2statmax	T2statdel	T2dyn0	T2dyn5
Unfinished	0.30	0.66	0.35	0.34	0.33
1	0.23	0.70	0.48	0.31	0.32
2	0.20	0.64	0.44	0.38	0.46
3	0.23	0.67	0.44	0.34	0.35
4	0.18	0.66	0.48	0.31	0.31
5	0.27	0.68	0.41	0.31	0.31
6	0.25	0.69	0.44	0.34	0.31
7	0.23	0.66	0.42	0.29	0.29
8	0.26	0.56	0.30	0.34	0.36
9	0.24	0.68	0.44	0.32	0.31
10	0.26	0.68	0.42	0.34	0.35
11	0.25	0.68	0.42	0.34	0.33
os1	0.23	0.66	0.43	0.29	0.29
os2	0.22	0.62	0.40	0.28	0.30

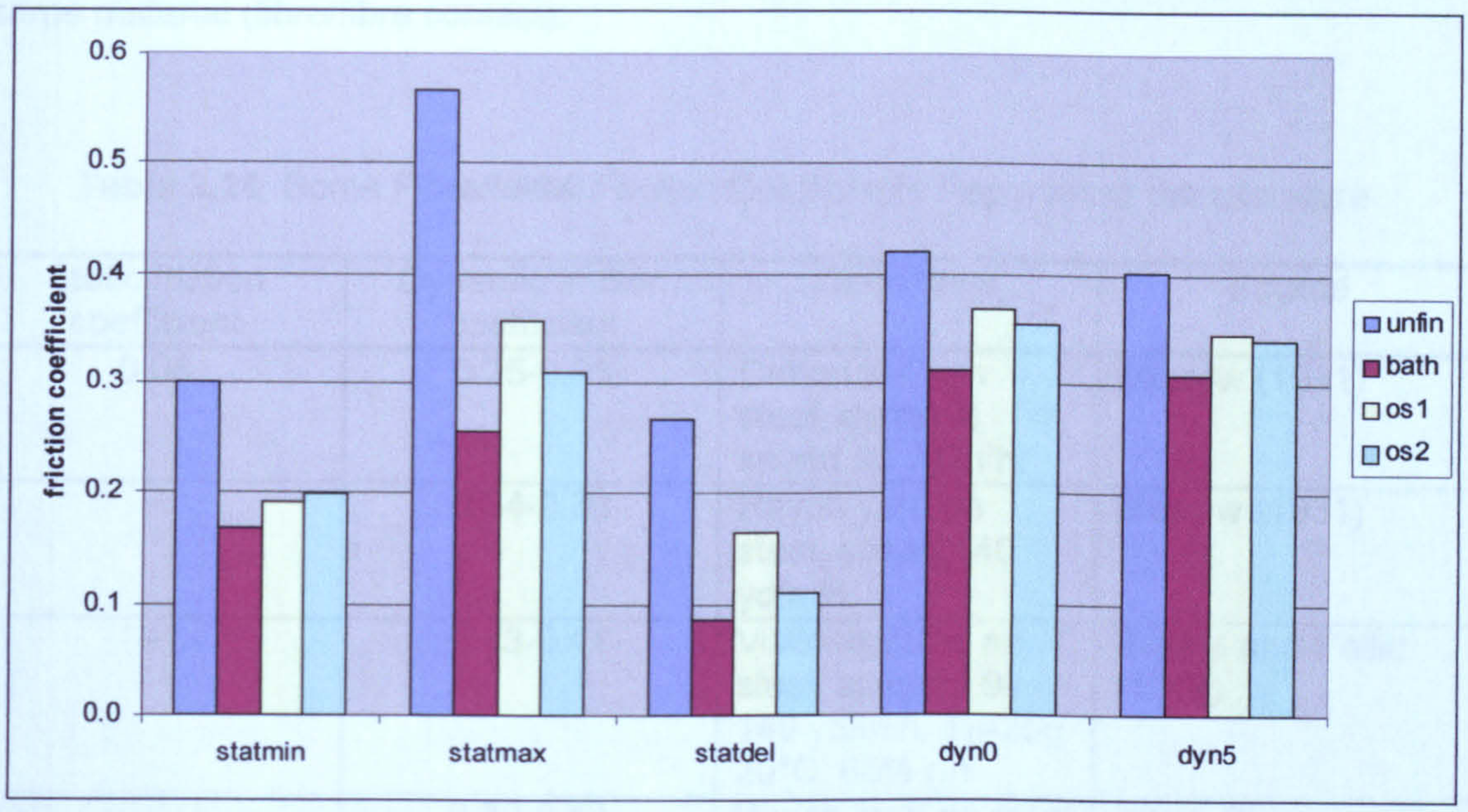


Figure 2.35 Friction Coefficient vs Finish Application Method (Fibre/Metal)

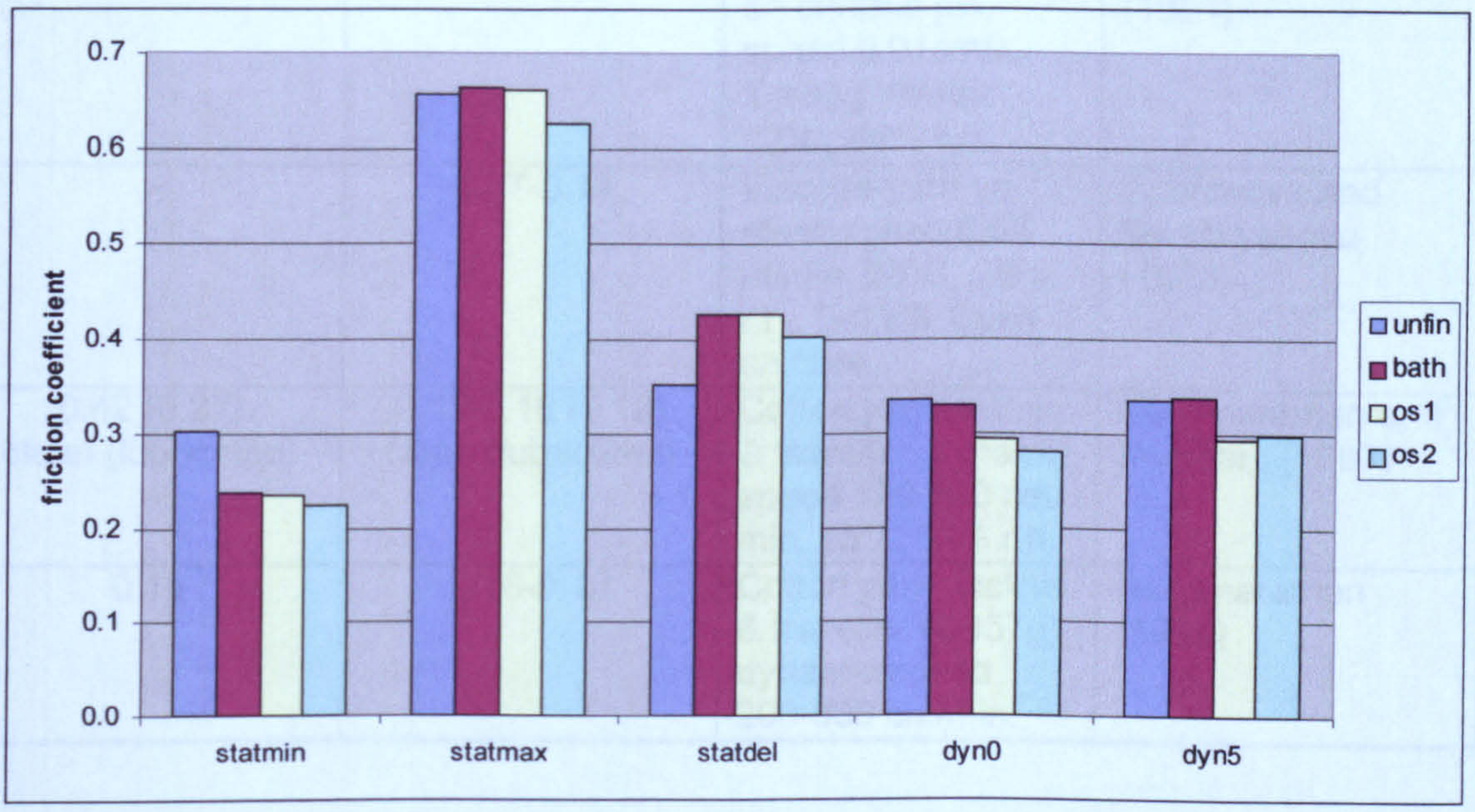


Figure 2.36 Friction Coefficient vs Finish Application Method (Fibre/Fibre)

2.2.5.2 Literature Friction Coefficients

Tables 2.28 and 2.29 show some of the literature values for the friction coefficients of cellulose fibres, yarns and fabrics, against metal (fibre/metal contact) and against the same material (fibre/fibre contact).

Table 2.28 Some Fibre/Metal Friction Coefficients Reported in the Literature

Static friction coefficient	Dynamic friction coefficient	Conditions	Source
0.06	0.25-0.35	Cotton yarn on steel, dynamic speed 60 yd/min.	Morrow (1931)
-	0.34-0.39	Rayon yarn on steel, speed 140 yd/min.	Morrow (1931)
-	0.13-0.41	Viscose yarns on steel, speed 1.9-140 yd/min, T_1=25g 20°C, 65% r.h.	Buckle and Pollitt (1948)
-	0.30-0.42	Rayon yarn on steel pin, speed 69m/ min, T_1=12g, 21°C, 65% r.h.	Anon, Shirley Institute Bulletin (1950)
0.80	-	Clean rayon yarn on chrome pin, speed 0.01cm/s, T_1=30g, θ=180°, 22°C, 65% r.h.	Fort Jr and Olsen (1961)
-	0.07-0.14	Viscose yarn on steel, speed 0.55 m/min, 20°C, 65% r.h., 0-0.5% finish on fibre.	Agafanova and Serebryakova (1973)
0.42 (0.27) clean (lubricated)	0.15-0.18 (0.13) clean (lubricated)	Cotton yarn, incline & traveller, dynamic speed 120-600 cm/ min, 35°C 60% r.h.	Kalyanaraman and Praksam (1987)
0.18	0.16-0.19	Cotton yarn, incline & traveller (0.357g), dynamic speed 200-800 cm/min.	Kalyanaraman (1988)

Table 2.28 Continued

Static friction coefficient	Dynamic friction coefficient	Conditions	Source
-	0.26-0.45 (0.20-0.3) initial (after 70 min.)	Cotton and viscose fabrics on steel, 20°C, 65% r.h.	Amirbayat and Cooke (1989)
0.26-0.45	-	Cotton yarn, incline & traveller, load 400 mN, 25°C, 65% r.h.	Subramaniam and Natarajan (1990)
0.20-0.25	-	Cotton knitted fabric on steel, sled on platform, 3-15kPa load, speed 0.3x 10^{-3} and 1.7x10^{-3} m/s, 20°C, 65% r.h.	Virto and Naik (1997)

Table 2.29 Some Fibre/Fibre Friction Coefficients Reported in the Literature

Static friction coefficient	Dynamic friction coefficient	Conditions	Source
0.27-0.30	0.14-0.18	Rayon fibre, torsion thread, loads 17-97 mg.	Gralen and Olofsson (1947)
0.33 (0.19) slip (stick)	-	Unfinished rayon.	Olofsson and Gralen (1950)
0.16-0.37 (0.09-0.30) slip (stick)	-	Finished rayon.	Olofsson and Gralen (1950)
0.28-0.57	0.20-0.36	Finished rayon tyre yarns.	Anon, British Rayon and Silk Journal (1954)
0.24-0.43	-	Cotton fibre fringes, speed 1.3cm/min, load 10-500g, 20°C, 65% r.h.	Lord (1955)
0.11-0.20	0.14-0.23	Finished rayon fibres, T_1=40mg, speed: static 3cm/min, dynamic 90cm/min, θ=180°.	Röder (1955)
0.72	-	Clean rayon yarn, speed 0.01cm/s, T_1=30g, θ=180°, 22°C, 65% r.h.	Fort Jr and Olsen (1961)

Table 2.29 Continued

Static friction coefficient	Dynamic friction coefficient	Conditions	Source
0.20-0.60	-	Finished rayon yarn, speed 0.01cm/s, T_1=30g, θ=180°, 22°C, 65% r.h.	Fort Jr and Olsen (1961)
0.17-0.34	0.22-0.47	Cotton fibres, T_1= 1.7-113.4mg, speed static 0.06cm/s dynamic 3.3cm/s, 22°C, 65% r.h.	Merkel (1963)
0.15-0.45	0.15-0.35	Rayon yarns from fabrics. Capstan, tension wt. 11.2-29.0g	Zurek *et al.* (1985)
0.37-1.24	0.24-0.56	Cotton fabric on fabric, 21°C, 65% r.h.	Carr *et al.* (1988)
0.22-0.41	-	Viscose yarns, load 100-400mN, 25°C, 65% r.h.	Subramaniam and Natarajan (1990)

2.2.5.3 Comparison of Measured and Literature Friction Coefficients

It is clear from Tables 2.28 and 2.29 that there is a wide range of fibre/metal and fibre/fibre friction coefficients reported in the literature. The coefficients obtained seem to depend on the conditions under which measurements were made e.g. fibre, fabric or yarn, and capstan, fibre fringe or sled and pulley methods. For cellulose fibres the relative humidity is important (see section 1.3.5). Also, there may be other factors to consider. In some studies the fibres or yarns were lubricated, in other cases they were unfinished or cleaned. In some work, it was not clear whether finish was used or not.

The maximum fabric/fabric friction coefficients reported by Carr *et al.* (1988) are high in comparison to other results using fibres and yarns. This is likely to be due to

mechanical interlocking of the yarn crowns in the fabric weave, which would provide a resistance force in addition to friction.

Overall, the friction coefficients produced in the present study are within the range of literature values for viscose and cotton. Specifically, the friction coefficients obtained for viscose in the present work (Tables 2.26 and 2.27) are in general agreement with viscose rayon, fibre and yarn, friction coefficients from the literature (Tables 2.28 and 2.29). Some of the fibre/fibre friction coefficients from the present study are a little higher than those reported in the literature, but not by more than a difference of 0.1. The static fibre/metal friction coefficient given by Morrow (1931) for clean rayon is higher than the coefficients found in the present work. Morrow's result is the only one found for comparison, and as some of the other literature friction coefficients show, there is not always agreement between workers.

Note, that only in the work of Olofsson and Gralen (1950) are stick and slip, static friction coefficients given separately. As in the present work, Olofsson and Gralen measured static (μ_s) and kinetic (μ_k) friction coefficients at the slip and brake points in the saw-tooth cycle (corresponding to T2statmax and T2statmin here).

Bowden and Tabor (1950) defined the static friction coefficient (μ_s) at the maximum point in the stick-slip cycle. Kinetic friction (μ_k) was defined at midway between the maximum and minimum stick-slip points.

El Mogahzy and Broughton (1993) used the middle positions between minima and maxima in the stick-slip pattern to produce smooth friction profiles for fibre fringes. Virto and Naik (1997) also used this approach on stick-slip responses from fabrics

sliding on metal and polymer surfaces, where the average of the maximum and minimum friction forces was used to calculate the friction coefficient.

Ajayi *et al.* (1995) defined a number of friction parameters in fabric sliding experiments. F_s was the force at the highest peak at the beginning of sliding motion, F_k was the mean force between peaks and troughs in the stick-slip cycle, F_s was the height of the stick-slip pulse (corresponding to T2statdel in the present study), F_n was the number of peaks per 5cm, F_p was the stick-slip pulse width and F_s-F_k was defined as the differential friction force.

There are a number of ways of expressing results from friction measurements. The most fruitful information is obtained when direct comparisons can be made between treatments. This requires a consistent measurement method, so in comparing one technique with another, it would be no surprise to find differences in the friction values of similar materials. Fortunately, in the present study a consistent measurement technique was used to compare different treatments on viscose fibres, and the friction data are in general agreement with the range of values produced from other studies.

2.3 ELECTRICAL RESISTANCE vs FINISH DEPOSITION CONDITIONS

It is known that electrostatic charging of fibres, fabrics and other textile assemblies can cause problems (Holme *et al.*, 1998). Sticking, clinging and spark discharging must be controlled for problems to be avoided. The addition of antistatic agents to fibre finishes is a common method employed.

There are questions as to whether electrical resistance measurement is suitable for evaluation of antistatic performance. In these experiments, however, resistance was

determined in relation to the finish deposition conditions. Fibres with a high resistance would be expected to retain charge whilst those with a higher conductivity (i.e. lower resistance) would be expected to dissipate charge and give fewer processing problems.

The finished fibres described in section 2.1.1 were conditioned at 20°C and 65% r.h. for at least 24 hours, since the electrical resistance of fibres, viscose and cotton in particular, is dependent on relative humidity and moisture regain (Morton and Hearle, 1993b). The resistance of 10cm long, 0.05g bundles of the fibres was measured by securing the ends between cleaned brass contacts (wiped with ethanol) across a 20mm gap and measuring the resistance with a Pye Megohmmeter, model 11801. Unfinished and oversprayed fibres were also conditioned and tested. The results are tabulated below.

Table 2.30 Electrical Resistance of Fibre Bundles

Sample	Date	Run	Resistance/G Ohms
Unfinished	04/03/97	1	6.0
		2	6.5
		3	7.0
		4	6.5
		5	7.5
		6	6.5
1	17/12/96	1	4.5
		2	4.0
		3	3.5
		4	4.0
		5	4.0
	04/03/97	1	3.5
		2	3.5
		3	4.0
		4	3.5
		5	4.0

Table 2.30 Continued

Sample	Date	Run	Resistance/G Ohms
2	17/12/96	1	0.1
		2	4.5
		3	4.0
		4	4.5
		5	4.5
	04/03/97	1	4.5
		2	4.0
		3	5.0
		4	4.0
		5	2.5
3	17/12/96	1	3.5
		2	4.5
		3	4.5
		4	6.5
		5	4.0
	04/03/97	1	4.0
		2	4.0
		3	4.5
		4	6.0
		5	4.0
4	17/12/96	1	3.5
		2	4.0
		3	5.0
		4	4.5
		5	4.0
	04/03/97	1	4.0
		2	4.5
		3	5.5
		4	5.5
		5	4.5
5	17/12/96	1	4.0
		2	4.0
		3	4.5
		4	4.0
		5	4.5
	04/03/97	1	4.5
		2	4.0
		3	4.5
		4	4.5
		5	3.5

Table 2.30 Continued

Sample	Date	Run	Resistance/G Ohms
6	17/12/96	1	4.0
		2	3.5
		3	3.5
		4	3.5
		5	3.5
	04/03/97	1	3.0
		2	3.5
		3	4.0
		4	4.0
		5	4.0
7	17/12/96	1	3.5
		2	3.5
		3	4.0
		4	6.5
		5	5.5
	04/03/97	1	3.5
		2	4.5
		3	5.0
		4	4.0
		5	4.0
8	17/12/96	1	4.0
		2	4.0
		3	4.0
		4	4.5
		5	4.0
	04/03/97	1	4.0
		2	4.0
		3	4.0
		4	4.5
		5	5.0
9	17/12/96	1	4.0
		2	4.5
		3	4.0
		4	4.0
		5	5.0
	04/03/97	1	4.5
		2	4.5
		3	4.0
		4	4.0
		5	4.5

Table 2.30 Continued

Sample	Date	Run	Resistance/G Ohms
10	17/12/96	1	4.0
		2	6.0
		3	5.0
		4	3.5
		5	4.0
	04/03/97	1	5.0
		2	3.5
		3	4.5
		4	4.0
		5	3.5
11	17/12/96	1	4.0
		2	5.0
		3	5.5
		4	5.0
		5	6.0
	04/03/97	1	4.0
		2	6.0
		3	5.0
		4	6.0
		5	5.5
os1	28/06/97	1	6.0
		2	6.5
		3	7.0
		4	6.5
		5	7.5
		6	7.0
os2	28/06/97	1	7.0
		2	7.5
		3	8.5
		4	7.0
		5	9.5
		6	6.5

Figure 2.37 represents the average results and 95% confidence intervals calculated from the data of Table 2.30.

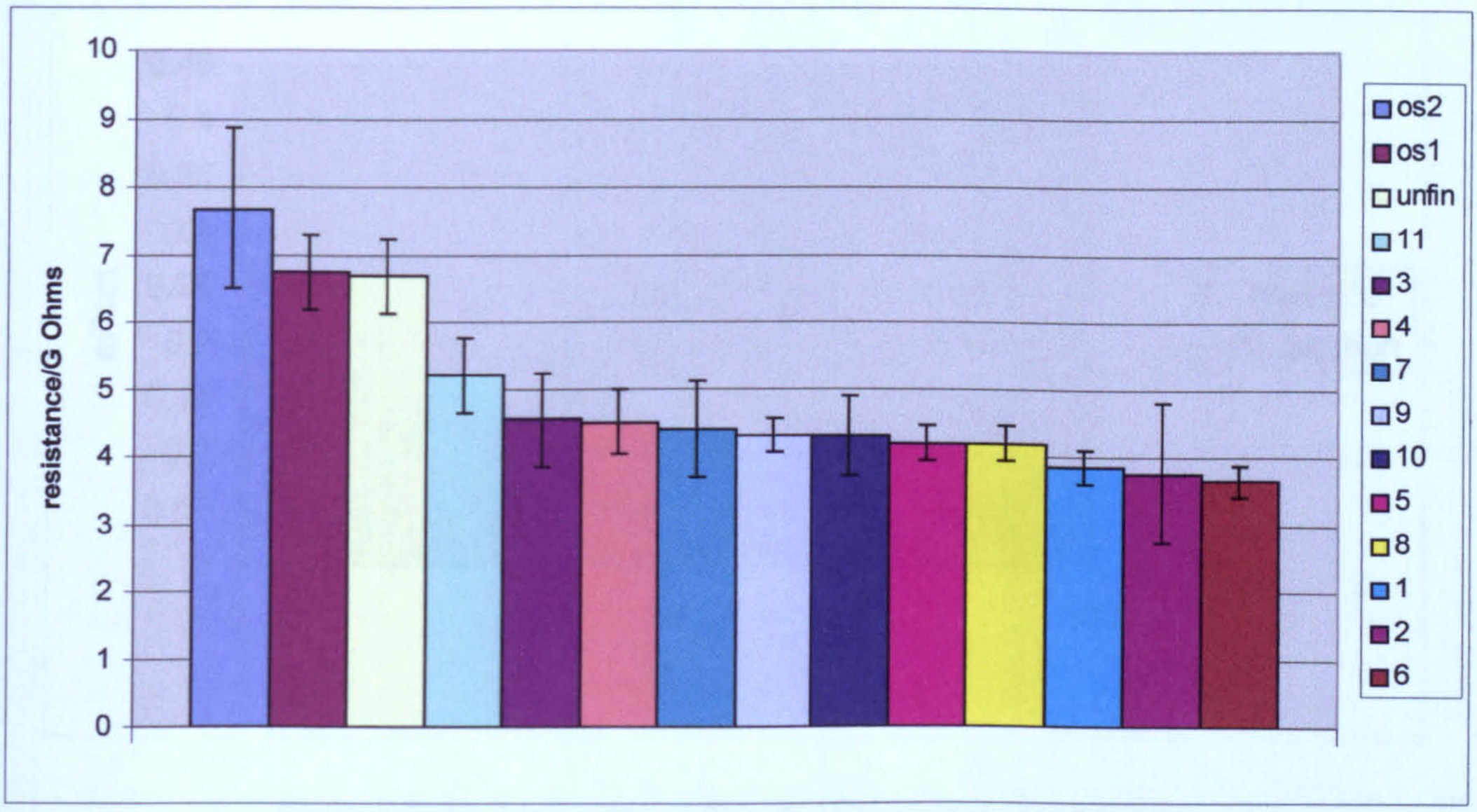


Figure 2.37 Electrical Resistance of Viscose Fibres

The mean resistance was calculated for each of the bath finished specimens from the designed deposition experiment. As in section 2.2.2.4, a half-normal plot was produced to determine whether the %092:P2DL in the emulsion (A), emulsion concentration (B), deposition temperature (C), deposition time (D) and the cross terms (AB=CD, AC=BD and AD=BC) had significant effects on the finished fibres' electrical resistance. Half-normal plots show whether a factor is significant in determining an effect. Factors which lie on, or close to the half normal line are random and could be generated by error. Factors away from the line are significant.

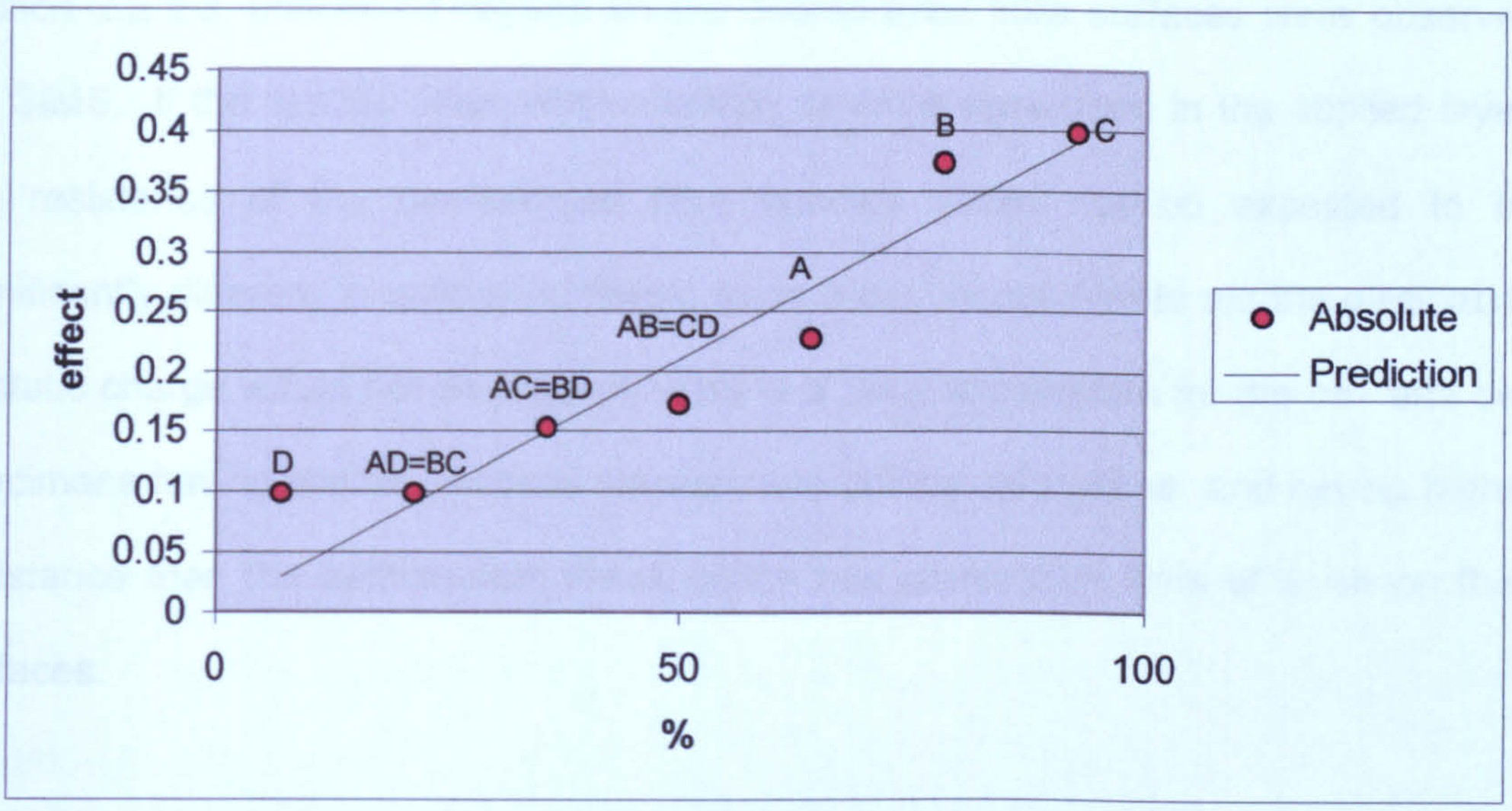


Figure 2.38 Half-normal Plot for Electrical Resistance

It is apparent that none of the deposition factors had a significant effect on the finished fibre resistance. Olofsson and Gralen (1950) observed no significant difference in the electrical resistance of viscose fibres, when various finishing treatments were applied. The present work is in agreement with Olofsson and Gralen's observation, and suggests that for bath finishing, it is not possible to change the electrical resistance of the fibres by altering application conditions.

Unsurprisingly, the resistance of the unfinished fibre was higher than that of the bath finished fibres. With no cationic surfactant (092) present to act as an antistat, charge accumulated during conversion to yarns would not be dissipated and problems could occur.

The oversprayed specimens (os1 and os2) showed the highest electrical resistances, although the total amount of finish extracted and %092 in the extract were no lower than some of the bath finished fibres (compare Tables 2.4 and 2.9). As mentioned in

section 2.2.2.3, unfinished regions on the oversprayed fibre surfaces were observed via SIMS. If the applied finish was in islands or there were gaps in the applied layer, the resistance of the oversprayed fibre bundles would not be expected to be significantly different to unfinished fibres, since a continuous film to aid the dissipation of static charge would not be present. This is a likely explanation for the os1 and os2 specimens having similar electrical resistance to unfinished viscose, and having higher resistance than the bath treated fibres, which had continuous films of finish on their surfaces.

The lowest electrical resistance was achieved when the fibres were finished by the bath application method, although the %092:P2DL in the emulsion, emulsion concentration, deposition temperature, and deposition time did not affect the finished fibre resistance significantly. It can be concluded that the conditions of the bath were not critical, but that bath application would be expected to give better control of static charge on finished fibres than overspray application or no finish at all.

2.4 CONCLUSIONS

With an appropriate calibration, SIMS was shown to be a viable tool in the direct analysis of the composition and distribution of a two component finish, comprising a lubricant and an antistat, applied to viscose fibres. The unknown surface composition of finished fibres was determined successfully using a calibration model.

In a designed experiment, with finish applied to viscose from a bath, SIMS was used to show that the surface composition of finished fibres did not reflect the bath composition. The dip time and temperature of the bath did not affect the composition of the deposited surface either.

The total amount of finish extracted from the viscose fibres depended on the bath emulsion concentration. A higher concentration produced more finish on fibre. The quantity of antistat relative to lubricant in the emulsion was also important. More antistat in the bath resulted in more antistat deposited through the fibre bulk.

The emulsion concentration in the bath was the only factor to affect static and dynamic fibre/metal friction. The higher the bath concentration, the lower the fibre/metal friction. The ratio of antistat to lubricant in the bath, the dip time and the bath temperature did not affect fibre/metal friction significantly.

Unlike fibre/metal friction, none of the finish bath variables (emulsion concentration, ratio of antistat to lubricant in the bath, the dip time and the bath temperature) had a significant effect on static or dynamic fibre/fibre friction.

Spraying finish onto viscose fibres resulted in unfinished regions. The surface composition and total amount of finish deposited did not reflect the quantity of finish in the sprayed emulsion.

Overall, bath application produced lower static and dynamic, fibre/metal friction than overspraying. Unfinished viscose fibres produced the highest friction forces and the largest stick-slip difference at low speed. The finish application method made little difference to fibre/fibre friction and unfinished viscose produced comparable friction forces to finished fibres.

Considering all of the fibres studied, the average static fibre/fibre friction forces were greater than those produced by static fibre/metal friction, although there was little difference between fibre/metal and fibre/fibre dynamic friction.

The friction coefficients produced in this work are in general agreement with the range of values from the literature, however, the friction coefficient obtained depends on the method of measurement and a variety of techniques were used in the literature studies.

The bath conditions (emulsion concentration, ratio of antistat to lubricant in the bath, the dip time and the bath temperature) did not affect the electrical resistance of the finished viscose fibres significantly. Oversprayed fibres had higher electrical resistance similar in magnitude to unfinished fibre. The high resistance of oversprayed fibres was probably due to discontinuous coverage of finish, and in particular, of antistat.

CHAPTER 3

INVESTIGATION OF WET LUBRICANTS FOR THE REDUCTION OF ABRASION DAMAGE TO FABRIC IN CONTACT WITH METAL

3.1 INTRODUCTION

Friction and abrasion during wet processing of fabrics can give rise to a number of different problems. During dyeing and finishing, wet fabrics can be dragged over metal machine surfaces, which creates damage and imperfections on the fabric surface. When dyeing and finishing fabrics in rope form, folds can develop and these are prone to excessive abrasion. Such damage is manifested as "crows feet" and white line creases, which are a particular problem when processing cellulosic fabrics. Dark shades accentuate the problem by showing up the lighter abraded regions.

Lubricant additives are available for fabric processing but there is little evidence in the literature to suggest thorough investigation into the mechanisms by which these lubricants reduce fabric damage. In the present study, the friction reducing properties of a range of typical chemicals used in available lubricants (e.g. wax dispersions, surfactants and polyacrylics) were evaluated. Novel lubricants (block copolymers and bio-polymers) were also studied. An attempt was made to relate wet friction to abrasion damage between wet fabric and metal surfaces.

3.2 FRICTION REDUCING PROPERTIES OF LUBRICANTS IN AQUEOUS SYSTEMS

3.2.1 Experimental

The friction measuring apparatus was the same as used for the fibre friction experiments (see section 2.2.1). The specimens used here were 5cm x 1cm strips of lyocell fabric, consisting of Courtaulds lyocell fibres (1.7 dtex) in a Santanderina Q7027, 2/1 twill construction. The fabric had been previously scoured and so experiments were done on prepared fabric (i.e. ready for dyeing and finishing). The warp face of the fabric was in contact with the stainless steel friction pin in each experiment.

Fabric specimens were saturated with lubricant solution, using several drops from a pipette, before measuring static friction. Usually, the static friction traces required a few minutes to reach a steady plateau value, hence the static friction force (T2stat5) was measured after 5 minutes had elapsed since the start of the test. In the measurement of dynamic friction, a few drops of lubricant solution were applied between the fabric and metal surfaces, until a meniscus formed as the metal pin was set to rotate. Dynamic friction forces (T2dyn0 and T2dyn5) were measured at the moment the friction pin started to rotate (and a lubricant meniscus was formed) and after 5 minutes of rotation.

A typical friction chart from the wet fabric/metal experiments is shown in Figure 3.1. The upper and lower traces correspond to dynamic (pin rotating at 0.5 ms^{-1}) and static (pin stationary) friction respectively. The scales on the x and y axes are time (minutes) and force (cN) respectively. The scale markers visible on the plot correspond to 5 minutes and 50cN. This particular trace was derived using distilled water as the lubricating liquid.

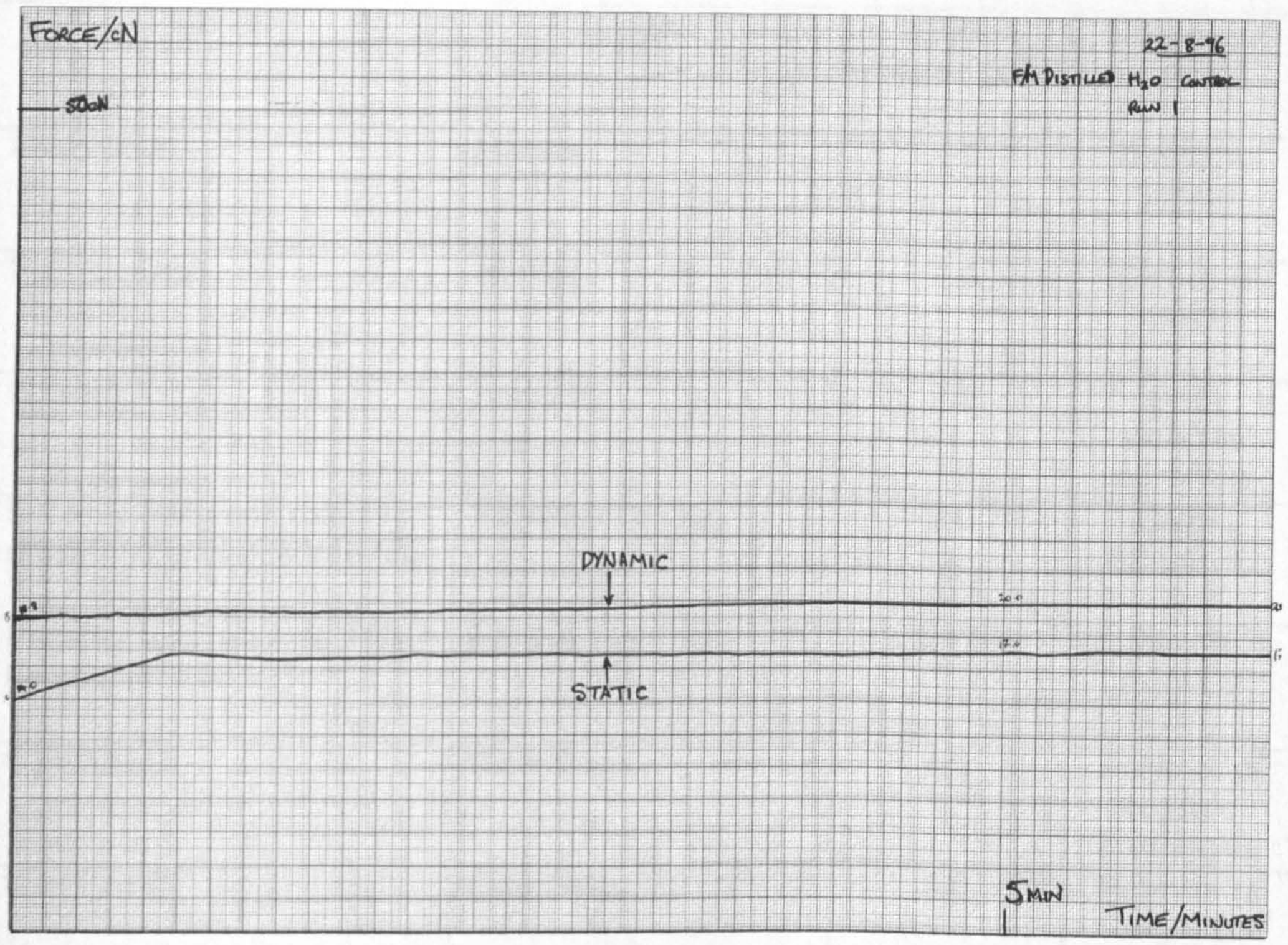


Figure 3.1 Typical Wet Fabric/Metal Friction Trace

The lubricant solutions used are listed in Table 3.1.

Table 3.1 Lubricant Fluids Used in Wet Friction Experiments

Lubricant	Source	Solution conc. gl^{-1}	Comments
60:40 Poly(acrylamide - acrylic acid) copolymer sodium salt, MW >10m	Polysciences Inc.	0.1	Coded PAm/PAA 1
30:70 Poly(acrylamide - acrylic acid) copolymer sodium salt, MW 200k	Polysciences Inc.	0.1	Coded PAm/PAA 2
90:10 Poly(acrylamide - acrylic acid) copolymer sodium salt, MW 200k	Polysciences Inc.	0.1	Coded PAm/PAA 3

Table 3.1 Continued

Lubricant	Source	Solution conc. gl^{-1}	Comments
Oleic DEA	Henkel	1.0	Diethanol amide
Palmitic DEA	Henkel	1.0	Diethanol amide
Leomin	Hoechst	2.0	PEG stearate/ palmitate
5:1 Poly (ethylene oxide – propylene oxide), MW 8750	Polysciences Inc.	2.0	Coded PEO/PPO
Paraffin wax (mp 109°C) + Leomin (emulsifier)	Henkel, Hoechst	2.0 + 0.5	Wax is Loxiol G22
Cibafluid C	Ciba Geigy	4.0	Polymer of organic acid/amide
Cibafluid C	Ciba Geigy	5.0	Polymer of organic acid/amide
Perilan VF	Dr Petry GmbH	4.0	Polymer of organic acid/amide
Perilan VF	Dr Petry GmbH	5.0	Polymer of organic acid/amide
Brij 30	Fluka	5.0	$C_{12}EO_4$
DSDMAC	Fluka	5.0	Di stearyl di methyl ammonium chloride
SDS	BDH	5.0	Sodium dodecyl sulphate
Persil non-bio	Lever	5.0	Washing powder
Comfort	Lever	5.0	Fabric conditioner

Table 3.1 Continued

Lubricant	Source	Solution conc. gl^{-1}	Comments
Sandoperm MEJ	Clariant UK	5.0	Siloxane fabric softener
Xanthan	Courtaulds Chemicals	4.0	Poly saccharide gum
Xanthan	VTT	5.0	Poly saccharide gum
Gellan	VTT	5.0	Poly saccharide gum
Welan	VTT	5.0	Poly saccharide gum
Bacterial polysaccharide	VTT	5.0	Poly saccharide gum
Dye liquor	Various	-	Dye, salts & sequestrant
Dye liquor + PAm/PAA 2	Various	0.1	-
Dye liquor + Cibafluid C	Various	4.0	-
Dye liquor + Perilan VF	Various	4.0	-
Dye liquor + wax/leomin	Various	2.0 + 0.5	-

The lubricants and concentrations shown in Table 3.1 were selected to be representative of the types of compounds used in commercially available systems (Barringer, Jr., 1994, Danner and Palacin, 1995, Kuhn *et al.*, 1995, Kuhn and Ouziel, 1995). Cibafluid C and Perilan VF are textile lubricants already in common use.

Brij 30, DSDMAC and SDS are common non-ionic, cationic and anionic surfactants used here at concentrations similar to the recommended dilutions for detergents and fabric conditioners (Persil non-bio and Comfort).

Sandoperm MEJ is a silicone softener used in fabric finishing and it would be expected to deposit on the fabric and modify the surface friction. Here it is used at a typical fabric finishing concentration.

The gums (xanthan, gellan and welan) are often used as emulsifying, stabilising, thickening, suspending and gelling agents in the food and other industries. The bacterial polysaccharide also modifies viscosity in aqueous solution. This polysaccharide occurs through bacterial contamination in the paper making industry. The resulting slime causes problems in paper manufacture and quality if contamination is not controlled. The gums and bio-polymer were in solution at concentrations which modified viscosity (thickening effect), yet allowed immersion of fabric. The gum and bio-polymer concentrations (between 4 and $5gl^{-1}$) were also the same as some of the other classes of lubricant tested.

Selected lubricants were tested in dye liquor rather than in water, to represent conditions during fabric dyeing. Some wet textile processes such as scouring, soaping-off or softener application use simple solutions of detergent or softener. In dyeing, however, other components such as salts, levelling agents and sequesterants could be present and the lubricant performance may not be the same as in a simple aqueous solution.

Solutions were made by stirring the appropriate quantities of lubricant into distilled water until dissolved. The gums and bacterial polysaccharide were sprinkled gently into cold water whilst stirring vigorously until dissolved, otherwise a gelatinous mass tended to form and prevent further dissolution.

To make the wax dispersion, the wax and leomin (emulsifier) were heated together and stirred gently until the wax was molten. This was poured into boiling water under high shear mixing using a Silverson high shear mixer. A dispersion resulted which was sufficiently stable for the experiments.

The dye liquor was made to represent a typical dyebath composition used for dyeing cellulosic fabrics. Components were added to water at the concentrations shown in Table 3.2, and agitated until dissolved.

Table 3.2 Dye Liquor Composition

Component	Source	Concentration gl^{-1}
Soda ash (sodium carbonate)	Ellis & Everard	20
Glaubers salt (sodium sulphate)	Ellis & Everard	55
Zetex PAL-N (sequestrant)	BASF	3
Procion navy H-ER 150 dye	Zeneca	1

Cibafluid C, Perilan VF and PAm/PAA 2 were added to dye liquor such that the concentrations were as shown in Table 3.1. To make the wax/leomin and dye liquor mixture, the dye liquor components shown in Table 3.2 were added to the aqueous wax dispersion to obtain the required concentrations.

Control samples were run using water as the wetting liquid. In addition, experiments were done with poly(ethylene) film, attached with double sided adhesive tape, covering

the metal pin. This was done in order to simulate the effect of coating the metal surface with a low friction polymer.

3.2.2 Friction Results From the Various Wetting Liquids

Results of the fabric-to-metal friction experiments for the various lubricant systems and dyebath components are listed in Table 3.3. There was no stick-slip behaviour (see Figure 3.1) so the static friction force (T2stat5) was measured after five minutes when a steady force was reached. As before, in the fibre friction experiments (section 2.2.2), dynamic friction forces were measured as soon as the metal pin started to rotate (T2dyn0) and after five minutes of rotation (T2dyn5).

Table 3.3 Wet Fabric/Metal Friction Forces (in cN)

Liquid	Date	Run	T2stat5	T2dyn0	T2dyn5
Water	30/05/96	1	17.3	19.4	22
		2	17.1	19.3	21.2
		3	16.5	19	21.4
		4	17.6	19.4	21.3
		5	16.8	19	21.8
Water	23/07/96	1	16	19.5	20.8
		2	14.5	20.2	20.1
		3	14.6	18.8	20.3
		4	15.2	18.8	19.9
		5	15.4	18.8	20
Water	22/08/96	1	17	18.8	20
		2	17	19	20
		3	15.7	18.6	19.8
		4	16	19.3	20.4
		5	15.4	19.2	20.3
Water	17/09/96	1	17	18.4	19.5
		2	16	18.1	19.4
		3	15.8	18.4	19.2
		4	16.3	18.6	19.5
		5	15.5	18.4	19.5
Water	13/11/96	1	16.3	18.9	20
		2	18.4	19.4	20.5
		3	16.3	19.3	20.8
		4	19.3	20	21.3
		5	17.7	19.1	20.7

Table 3.3 Continued

Liquid	Date	Run	T2stat5	T2dyn0	T2dyn5
Water	11/12/96	1	16.7	19	20.1
		2	17.6	19.7	20.9
		3	16.3	19.7	20.7
		4	17.3	20.1	21.3
		5	16.4	19	20.5
Water	02/12/97	1	16	19	19
		2	14.5	18	19.5
		3	14.5	18.5	19
		4	13.5	18	19
		5	14.5	19	20
2g/l wax 0.5g/l leomin	18/07/96	1	13	17.6	18.9
		2	14	18.1	19.2
		3	13.8	17.6	19.7
		4	13.9	17.8	19.6
		5	13.8	17.8	18.8
2g/l wax 0.5g/l leomin	22/08/96	1	13.7	18.3	19.1
		2	14.3	18.7	19.1
		3	14.1	18.6	18.8
		4	13.9	17.8	18.3
		5	14.2	17.3	18.3
5g/l SDS	30/05/96	1	18.9	18.7	21.6
		2	17.9	18.4	21.2
		3	17.4	17.6	19.7
		4	17.5	17.4	21.3
		5	17.5	19.4	21.8
5g/l SDS	16/09/96	1	15.3	16.4	17.9
		2	16.2	17	19
		3	16.5	17.2	19.1
		4	16.5	17	19.1
		5	16.4	17.2	19
5g/l Brij30	30/05/96	1	18	19.4	23.9
		2	18	17.2	20.6
		3	18.1	18.7	21.8
		4	18.7	18.8	21.4
		5	16.1	18.9	21.3
5g/l Brij30	17/09/96	1	16.8	17.9	19.8
		2	16.8	17.9	19
		3	16.2	17	18.8
		4	16.7	17.8	19.5
		5	16.9	17.8	19.8
5g/l DSDMAC	29/05/96	1	13.5	18.8	21.4
		2	14.4	18.4	20.4
		3	14.2	17.4	20.2
		4	14.4	17.9	20.6
		5	14.4	18	21.2

Table 3.3 Continued

Liquid	Date	Run	T2stat5	T2dyn0	T2dyn5
5g/l DSDMAC	12/09/96	1	13.6	18	18.9
		2	14.4	17.6	19.3
		3	14	17.8	19.2
		4	14	18	19.3
		5	14.8	18	19.2
5g/l Cibafluid C	31/05/96	1	15.1	18.4	20.9
		2	16.2	18.8	20.8
		3	16.4	18.2	20.4
		4	17	19	20.7
		5	16.8	18.7	20.8
4g/l Cibafluid C	18/09/96	1	15.6	18.5	19
		2	14.6	18.6	19.1
		3	16.2	19	19.2
		4	15.8	19.2	19.6
		5	15.9	18.7	19.4
5g/l Perilan VF	31/05/96	1	16.6	18.6	20.2
		2	18.1	19.7	21.2
		3	18.2	19.8	20.9
		4	16.8	19	20.9
		5	17.7	19.8	21.4
4g/l Perilan VF	18/09/96	1	14.5	18.3	18.8
		2	16.4	18.7	19.1
		3	15.3	18.7	19.3
		4	14.9	18.5	19
		5	15.4	18.2	18.8
PE film & water	31/05/96	1	12.7	18	18.7
		2	13.5	18.2	19
		3	13.2	17.8	19.2
		4	13.3	18.2	18.8
		5	13.7	18.2	18.9
1g/l oleic DEA	26/07/96	1	13.3	19.8	19.9
		2	13.9	19.4	20.1
		3	13.7	19	20
		4	15	19.7	21.1
		5	14	19.3	20.3
1g/l palmitic DEA	25/07/96	1	13.8	19	20
		2	14.3	19.4	19.9
		3	14.9	19.4	20.1
		4	14.1	19	19.8
		5	15.5	19.8	20.3
2g/l leomin	25/07/96	1	14.6	18.8	20
		2	14.2	18.3	20.2
		3	14.8	18.4	20.6
		4	14.9	18.7	20.6
		5	14.6	18.3	20

Table 3.3 Continued

Liquid	Date	Run	T2stat5	T2dyn0	T2dyn5
2g/l PEO/PPO	23/07/96	1	15.2	17.9	19.2
		2	14.9	17.7	19
		3	14.5	17.4	19
		4	14	17.3	18.7
		5	14.7	17.5	18.9
PAm/PAA 1	23/08/96	1	14.7	18.4	19
		2	15.2	18.3	19.2
		3	14.8	18.4	19.3
		4	14.9	18.8	19.5
		5	15.1	17.5	18.8
PAm/PAA 2	10/09/96	1	15	17.9	18.7
		2	15.1	17.7	18.6
		3	15.6	17.6	18.8
		4	14.8	18.5	19.3
		5	14.7	18	18.7
PAm/PAA 3	12/09/96	1	13.5	18	19.2
		2	14.7	18	18.6
		3	13.8	18.1	19.2
		4	14.5	18.4	19.1
		5	14.7	18	19.1
5g/l Comfort	03/10/96	1	13	17.6	18.8
		2	14	18.5	19.2
		3	14.8	18.6	19.2
		4	14.7	18.6	19.2
		5	14.3	18.6	19.3
5g/l Persil non-bio	03/10/96	1	15.9	17.9	18.8
		2	16.2	17.9	19
		3	16.2	18	19.1
		4	16.8	20	19.6
		5	16.7	18.5	19.4
5g/l Sandoperm MEJ	03/10/96	1	17.4	17.9	19.2
		2	13.3	17	18.1
		3	12.6	16.6	18.2
		4	13.2	17.6	18.6
		5	12.7	17.5	18.5
4g/l Xanthan gum	29/08/96	1	14.6	19	20
		2	15.3	18	19.6
		3	15.5	18.5	19.7
		4	15.5	18.6	20.6
		5	16.4	18.5	20.9
5g/l Xanthan	05/12/97	1	16.5	17	23
		2	16	19	23.5
		3	17	19.5	23
		4	16.5	18.5	24.5
		5	17	21	26.5

Table 3.3 Continued

Liquid	Date	Run	T2stat5	T2dyn0	T2dyn5
5g/l Bacterial polysaccharide	05/12/97	1	18.5	19.5	21
		2	19	19.5	21.5
		3	18.5	19	20
		4	19.5	19	20.5
		5	19.5	19	19.5
5g/l Welan	12/12/97	1	19	19	25
		2	18	20	24.5
		3	18.5	19	23.5
		4	19	19.5	23
		5	18.5	19	24.5
5g/l Gellan	12/12/97	1	18.5	20	23
		2	18.5	21.5	28
		3	18.5	19.5	25
		4	17.5	19	26
		5	17.5	19.5	24.5
Dye liquor	15/10/96	1	14.6	15.7	16.8
		2	15.6	16.4	17
		3	15.9	16.2	17.7
		4	16.2	16.7	18
		5	16.2	17	18.4
Dye liquor	13/11/96	1	17.4	16.0	18.0
		2	17.9	17.4	18.2
		3	18.4	17.9	18.4
		4	18.0	17.5	18.5
		5	17.8	18.2	18.8
Dye liquor+Perilan VF	14/11/96	1	17.9	17.6	18.1
		2	18.2	18	18.6
		3	17.8	17.8	18.5
		4	18	17.7	18.7
		5	17.6	17.8	18.5
Dye liquor+Cibafluid C	14/11/96	1	17.6	18.2	18.9
		2	17.2	17.4	18.5
		3	17.7	17.9	18.5
		4	17.8	18.6	18.8
		5	18.5	18	18.7
Dye liq+wax/leomin	15/10/96	1	17	17.7	18.6
		2	17	17.5	18.7
		3	17.2	17	18.1
		4	17.2	17.7	18.7
		5	17.1	17.1	18.4
Dye liq+wax/leomin	04/12/96	1	17.3	17.3	18.3
		2	17.6	17.6	19
		3	17.8	18	18.6
		4	17.7	17.8	18.4
		5	17.8	17.9	19.1

Table 3.3 Continued

Liquid	Date	Run	T2stat5	T2dyn0	T2dyn5
Dye liq+PAm/PAA 2	04/12/96	1	18.6	17.9	18.8
		2	18	17.8	18.8
		3	17.8	17.8	18.6
		4	18.4	18	19
		5	18.4	17.5	18.5

3.2.3 Statistical Analysis and Discussion of the Wet Fabric/Metal Friction Results

3.2.3.1 Analysis of Results

The wet fabric/metal friction results were analysed using Minitab (Version 11 for Windows). The Fisher's least significant difference (LSD) tool enabled the results from the various liquids to be ranked and grouped (95% confidence). This method of analysis was preferred to the multiple range tests used in section 2.2.3, since the number of replicates for some of the liquids was more than five. Use of the multiple range test is straight forward only if the number of replicates for each treatment is the same. The Minitab software is a convenient way of dealing with several treatments, with different numbers of replicates.

Tables 3.4 to 3.6 represent the output from the comparison tests. The solid bars link liquids which gave similar friction results and separate those which were different with 95% confidence. All mean friction forces are in cN units.

Table 3.4 Grouping of T2stat5 Wet Fabric/Metal Forces (95% Confidence)

rank	liquid	T2stat5 (cN)
1	PE film & water	13.28
2	5g/l Sandoperm MEJ	13.84
3	2g/l wax 0.5g/l leomin	13.87
4	1g/l oleic DEA	13.98
5	5g/l Comfort	14.16
6	5g/l DSDMAC	14.17
7	0.1g/l PAm/PAA 3	14.24
8	1g/l palmitic DEA	14.52
9	2g/l leomin	14.62
10	2g/l PEO/PPO	14.66
11	0.1g/l PAm/PAA 1	14.94
12	0.1g/l PAm/PAA 2	15.04
13	4g/l Perilan VF	15.30
14	4g/l Xanthan gum	15.46
15	4g/l Cibafluid C	15.62
16	water	16.23
17	5g/l Cibafluid C	16.30
18	5g/l Persil non-bio	16.36
19	5g/l Xanthan	16.60
20	dye liquor	16.80
21	5g/l SDS	17.01
22	5g/l Brij30	17.23
23	dye liq+wax/leomin	17.37
24	5g/l Perilan VF	17.48
25	dye liquor+Cibafluid C	17.76
26	dye liquor+Perilan VF	17.90
27	5g/l Gellan	18.10
28	dye liq+PAm/PAA 2	18.24
29	5g/l Welan	18.60
30	5g/l Bacterial polysaccharide	19.00

Table 3.5 Grouping of T2dyn0 Wet Fabric/Metal Forces (95% Confidence)

rank	liquid	T2dyn0 (cN)
1	dye liquor	16.90
2	5g/l Sandoperm MEJ	17.32
3	2g/l PEO/PPO	17.56
4	dye liq+wax/leomin	17.56
5	5g/l SDS	17.63
6	dye liquor+Perilan VF	17.78
7	dye liq+PAm/PAA 2	17.80
8	0.1g/l PAm/PAA 2	17.94
9	2g/l wax 0.5g/l leomin	17.96
10	5g/l DSDMAC	17.99
11	dye liquor+Cibafluid C	18.02
12	PE film & water	18.08
13	0.1g/l PAm/PAA 3	18.10
14	5g/l Brij30	18.14
15	0.1g/l PAm/PAA 1	18.28
16	5g/l Comfort	18.38
17	5g/l Persil non-bio	18.46
18	4g/l Perilan VF	18.48
19	2g/l leomin	18.50
20	4g/l Xanthan gum	18.52
21	5g/l Cibafluid C	18.62
22	4g/l Cibafluid C	18.80
23	5g/l Xanthan	19.00
24	water	19.02
25	5g/l Bacterial polysaccharide	19.20
26	5g/l Welan	19.30
27	1g/l palmitic DEA	19.32
28	5g/l Perilan VF	19.38
29	1g/l oleic DEA	19.44
30	5g/l Gellan	19.90

Table 3.6 Grouping of T2dyn5 Wet Fabric/Metal Forces (95% Confidence)

rank	liquid	T2dyn5 (cN)
1	dye liquor	17.98
2	dye liquor+Perilan VF	18.48
3	5g/l Sandoperm MEJ	18.52
4	dye liq+wax/leomin	18.59
5	dye liquor+Cibafluid C	18.68
6	dye liq+PAm/PAA 2	18.74
7	0.1g/l PAm/PAA 2	18.82
8	PE film & water	18.92
9	2g/l PEO/PPO	18.96
10	2g/l wax 0.5g/l leomin	18.98
11	4g/l Perilan VF	19.00
12	0.1g/l PAm/PAA 3	19.04
13	5g/l Comfort	19.14
14	0.1g/l PAm/PAA 1	19.16
15	5g/l Persil non-bio	19.18
16	4g/l Cibafluid C	19.26
17	5g/l SDS	19.97
18	5g/l DSDMAC	19.97
19	1g/l palmitic DEA	20.02
20	4g/l Xanthan gum	20.16
21	water	20.28
22	1g/l oleic DEA	20.28
23	2g/l leomin	20.28
24	5g/l Bacterial polysaccharide	20.50
25	5g/l Brij30	20.59
26	5g/l Cibafluid C	20.72
27	5g/l Perilan VF	20.92
28	5g/l Xanthan	24.10
29	5g/l Welan	24.10
30	5g/l Gellan	25.30

3.2.3.2 Discussion of Wet Fabric/Metal Friction Results

The lowest static friction force (after 5 minutes) resulted when the metal pin was covered with PE film. Some of the lubricant liquids also gave low static friction and these represented distinctly different types: Sandoperm MEJ (silicone softening agent), Comfort (fabric conditioner), DSDMAC (a major component in fabric conditioners), oleic DEA (surfactant) PAm/PAA3 (polymer solution) and wax/leomin (wax dispersion).

It is known from the literature that surfaces covered with close packed lubricant molecules, with hydrocarbon groups outermost, produce low friction forces when objects slide against them (Fort Jr. and Olsen, 1961, Fort Jr., 1962). This is probably the reason for fabrics feeling soft when conditioners or silicones are applied (Bräuer *et al.*, 1985, Jang and Yeh, 1993, Sandner, 1995). The friction forces between skin and fabric would be reduced, giving a smooth, soft feel. PE film is a hydrocarbon surface and so low friction is not unexpected. Particles of wax in the wax/leomin dispersion could act in a similar way to the polyethylene film if the sliding surfaces are separated by hydrocarbon wax particles.

Poly(acrylamide–acrylic acid) compounds such as PAm/PAA 3 are used commonly as dyeing and finishing lubricants, although the mechanism by which they reduce friction and damage, at such low solution concentrations, does not appear to be understood completely. Myers (1991) comments that lubricants with small amounts of surface-active additives, which have an adsorption interaction with the wear surface, can extend the lifetime of the system in operation. Such additives do not affect the bulk or viscous properties of the lubricant fluid, but they form a thin film at the sliding surfaces which gives protection when the lubricant film breaks down. Moore (1972) describes this effect as "oiliness" or "lubricity" and it is independent of the lubricant viscosity. The phenomenon is interpreted as boundary slip between the lubricating liquid and solid

surface, which contradicts the basic assumption of zero slip at boundaries between liquid and solid. When one of the surfaces bounding the lubricant is an elastomer (e.g. a polymer), the "oiliness effect" is far more important than in the case of metals. The lubricant is said to diffuse into the elastomer and create a lubricity layer. This effect may be relevant in explaining the mechanism of friction reduction by such low concentration solutions of poly(acrylamide–acrylic acid) compounds. The understanding of friction reduction by these compounds is by no means complete, and could form the basis for a separate investigation.

There were no obvious static friction trends for the rest of the lubricants. Some reduced static friction with respect to water (control), whilst others increased friction.

Dynamic friction behaviour between wet fabric and the metal pin was somewhat different from that observed with the static arrangement. Tables 3.5 (T2dyn0) and 3.6 (T2dyn5) show that dye liquor, and dye liquors containing lubricants, produced the lowest dynamic friction forces. Dye liquor alone gave the lowest friction result at t=0 and after 5 minutes. This is investigated further in section 3.2.5. As was the case for static friction, the Sandoperm MEJ solution also gave low dynamic friction forces. The gums (xanthan, gellan and welan) and the bacterial polysaccharide produced some of the highest dynamic friction forces. This could be due to an increase in fluid viscosity. Note that concentration is also important, as $4gl^{-1}$ xanthan produced lower dynamic friction than $5gl^{-1}$ xanthan and this is significant (95% confidence) for T2dyn5.

3.2.4 Wet Fabric/Metal Friction Coefficients

Using the capstan equation ($T_2/T_1=e^{\mu\theta}$) and the data of Table 3.3, friction coefficients were calculated. T1 was 10.19cN (10g weight, 0.34g clip and 0.05g of fabric) and the wrap angle $\theta = 90°$. The values are calculated from the average friction force over 5 results.

Table 3.7 Wet Fabric/Metal Friction Coefficients for Various Fluids

Liquid	T2stat5	T2dyn0	T2dyn5
Water	0.296	0.397	0.438
0.1g/l PAm/PAA1	0.244	0.372	0.402
0.1g/l PAm/PAA2	0.248	0.360	0.391
0.1g/l PAm/PAA3	0.213	0.366	0.398
1g/l oleic DEA	0.201	0.411	0.438
1g/l palmitic DEA	0.225	0.407	0.430
2g/l leomin	0.230	0.380	0.438
2g/l PEO/PPO	0.232	0.346	0.395
2g/l wax 0.5g/l leomin	0.196	0.361	0.396
4g/l Cibafluid C	0.272	0.390	0.405
5g/l Cibafluid C	0.299	0.384	0.452
4g/l Perilan VF	0.259	0.379	0.397
5g/l Perilan VF	0.344	0.409	0.458
4g/l Xanthan gum	0.265	0.380	0.434
5g/l Bacterial polysaccharide	0.397	0.403	0.445
5g/l Brij30	0.334	0.367	0.448
5g/l Comfort	0.209	0.376	0.401
5g/l DSDMAC	0.210	0.362	0.428
5g/l Gellan	0.366	0.426	0.579
5g/l Persil non-bio	0.301	0.378	0.403
5g/l Sandoperm MEJ	0.195	0.338	0.380
5g/l SDS	0.326	0.349	0.428
5g/l Welan	0.383	0.407	0.548
5g/l Xanthan	0.311	0.397	0.548
Dye liquor	0.318	0.322	0.362
Dye liq+PAm/PAA2	0.371	0.355	0.388
Dye liq+wax/leomin	0.340	0.346	0.383
Dye liquor+Cibafluid C	0.354	0.363	0.386
Dye liquor+Perilan VF	0.359	0.354	0.379
PE film & water	0.169	0.365	0.394

Suzuki *et al.* (1973) found the friction coefficient of wet cotton fabric sliding on a polypropylene film to be between 0.28 and 0.36 at normal loads between 0.5-3.0 kg,

fabric moisture contents between 0-300% and at a speed of 1cm/min. Suzuki's results are of a similar magnitude to the wet fabric/metal dynamic friction coefficients (T2dyn0 and T2dyn5) of Table 3.7, but note that some of the static coefficients (T2stat5) are much lower (<0.20).

3.2.5 The Effect of Individual Components of Dye Liquor on Wet Friction

Dye liquors gave the lowest wet, fabric/metal, dynamic friction forces. This was investigated further and the effect of the components of the dye liquor on static and dynamic friction was determined.

An experiment was designed using Minitab (Version 11 for Windows). The full factorial design involved 4 factors with 2 replicates and required 32 runs. The factors and their low and high levels (coded –1 and +1) are show in Table 3.8.

Table 3.8 Factors and Levels in Dye Liquor Friction Investigation

Factor	A	B	C	D
Name	Soda ash conc.	Glaubers salt conc.	Zetex PAL-N conc.	Procion navy H-ER 150 conc.
Low level (-1)	0 gl^{-1}	0 gl^{-1}	0 gl^{-1}	0 gl^{-1}
High level (+1)	20 gl^{-1}	55 gl^{-1}	3 gl^{-1}	1 gl^{-1}

The randomised experiment design and run order produced using Minitab is shown in Table 3.9.

Table 3.9 Run Order in Dye Liquor Friction Investigation

Run	Level of A	Level of B	Level of C	Level of D
1	1	1	1	1
2	-1	-1	-1	1
3	-1	1	-1	1
4	1	1	1	-1
5	-1	-1	-1	-1
6	1	-1	1	1
7	1	-1	1	1
8	-1	-1	-1	-1
9	1	-1	1	-1
10	1	1	1	-1
11	1	-1	-1	1
12	-1	-1	1	-1
13	-1	1	-1	-1
14	1	-1	-1	-1
15	-1	-1	1	-1
16	-1	1	1	1
17	1	-1	1	-1
18	-1	-1	1	1
19	-1	1	1	-1
20	-1	1	-1	-1
21	1	1	-1	1
22	-1	-1	-1	1
23	-1	1	1	-1
24	1	-1	-1	-1
25	1	1	-1	1
26	1	1	-1	-1
27	-1	-1	1	1
28	1	-1	-1	1
29	1	1	-1	-1
30	-1	1	-1	1
31	-1	1	1	1
32	1	1	1	1

Friction force (T2) values from the designed experiment are summarised in Table 3.10.

Table 3.10 Friction Force Values from Dye Liquor Friction Investigation (cN)

Run	T2stat5	T2dyn0	T2dyn5
1	17.0	16.5	17.5
2	20.0	19.0	20.0
3	16.0	16.0	17.0
4	19.0	18.5	20.0
5	18.5	19.5	21.0
6	18.5	18.0	19.0
7	18.5	18.0	19.5
8	19.5	20.0	22.5
9	19.5	19.5	21.5
10	20.5	19.5	20.5
11	18.5	18.0	19.0
12	20.0	20.0	21.5
13	18.0	18.0	20.0
14	19.5	19.5	21.5
15	21.0	21.0	21.5
16	16.5	16.5	17.0
17	19.0	18.5	21.0
18	20.0	19.5	20.0
19	16.5	18.0	20.0
20	16.5	17.0	19.0
21	16.0	15.5	17.0
22	17.0	18.0	19.0
23	16.5	17.5	19.0
24	18.5	19.0	21.0
25	17.5	16.5	17.0
26	19.5	18.5	19.5
27	20.0	19.5	20.5
28	17.5	17.0	18.5
29	20.0	19.0	20.5
30	17.0	17.5	18.0
31	17.5	16.5	17.5
32	17.5	16.5	17.0

The friction force data from the designed experiment were analysed using a fractional factorial fit on Minitab. This produces the estimated effects of each of the factors (A, B, C and D) and of the interactions (e.g. AB, AC, ABC, ABCD etc.). The main effect is the average change in response (friction force) when the factor (A, B, C or D) is changed

from its low level (-1) to its high level (+1). The main effects of the factors A, B, C and D are shown in Figures 3.2 to 3.4.

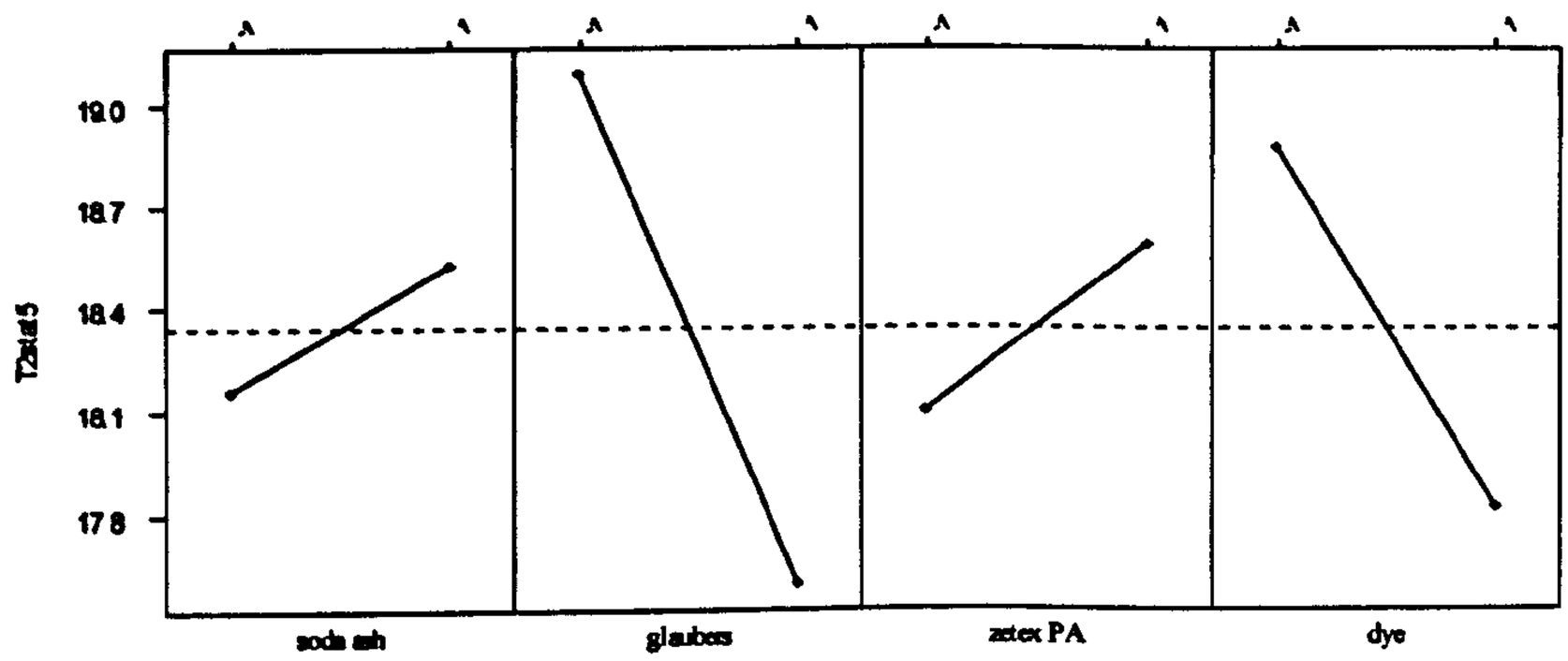


Figure 3.2 Main Effects of Dyebath Components on T2stat5

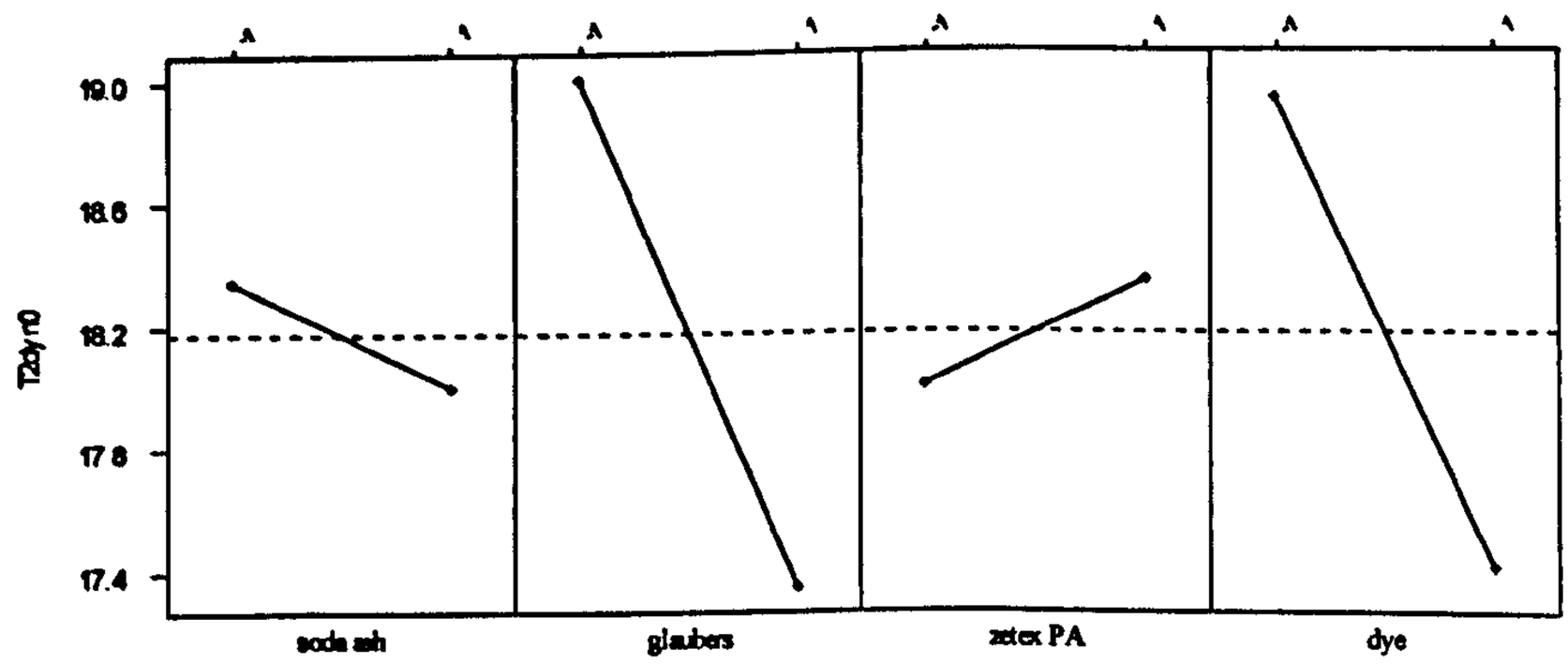


Figure 3.3 Main Effects of Dyebath Components on T2dyn0

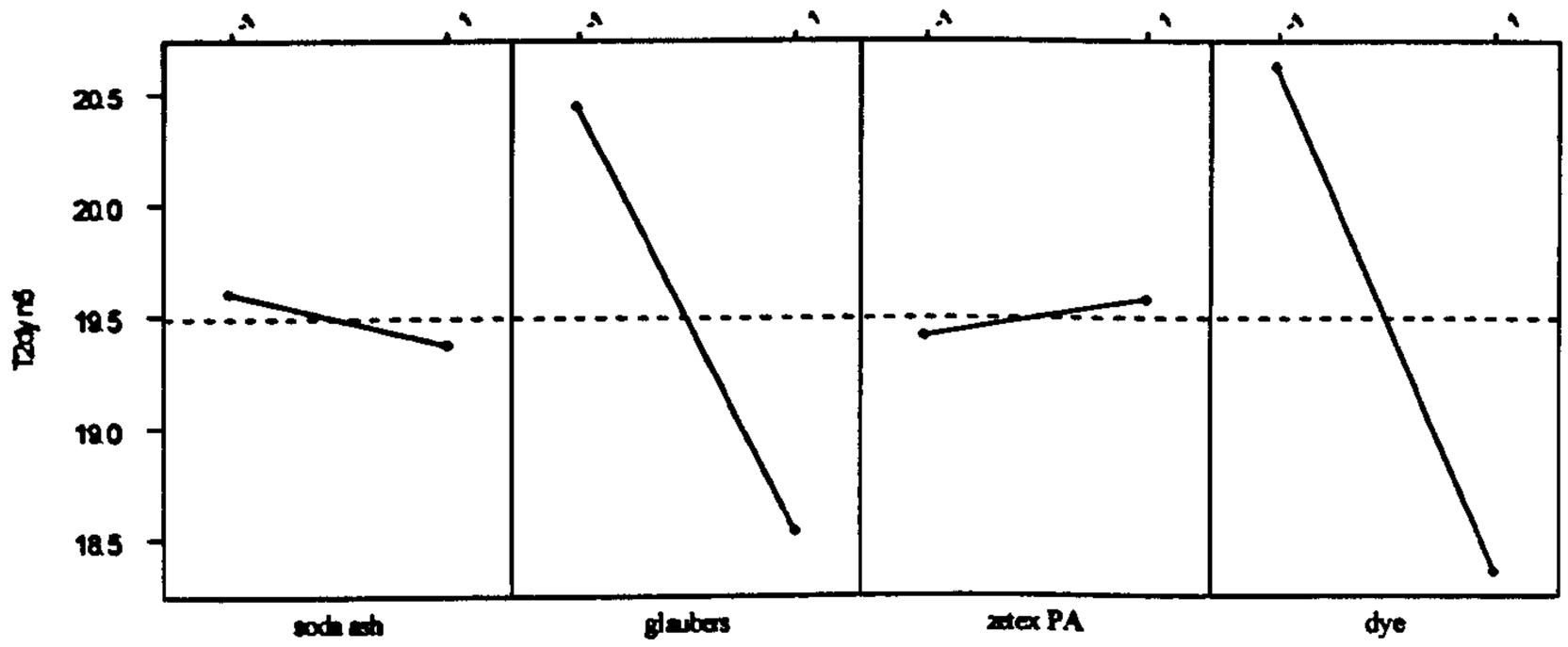


Figure 3.4 Main Effects of Dyebath Components on T2dyn5

A convenient method of determining which terms are significant, is to display their effects on a Pareto chart. Figures. 3.5 to 3.7 are Pareto charts showing the effect of the factors and interactions on T2stat5, T2dyn0 and T2dyn5. Terms which extend beyond the dotted line are deemed significant with 99% confidence (alpha = 0.01).

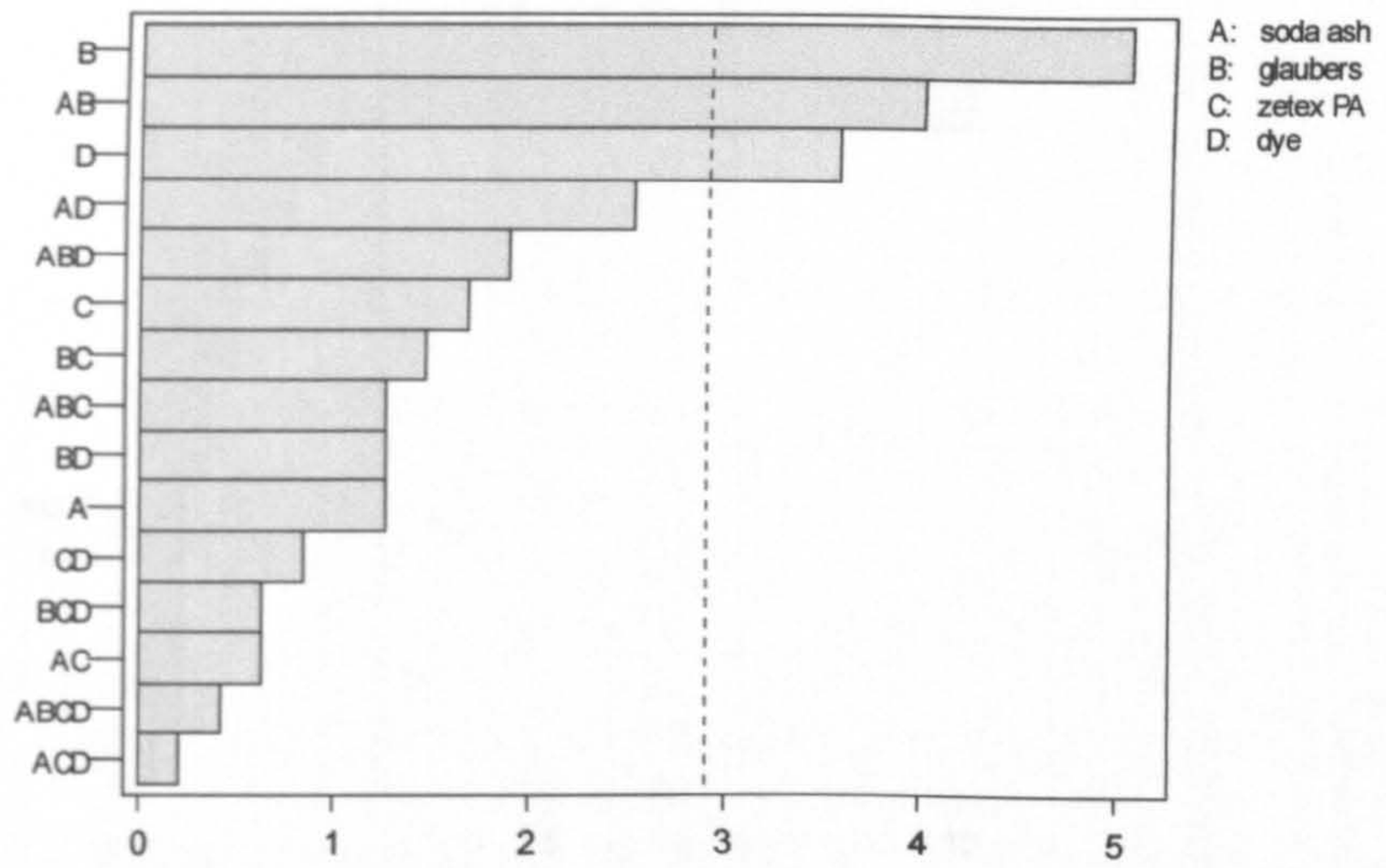


Figure 3.5 Pareto Chart for T2stat5

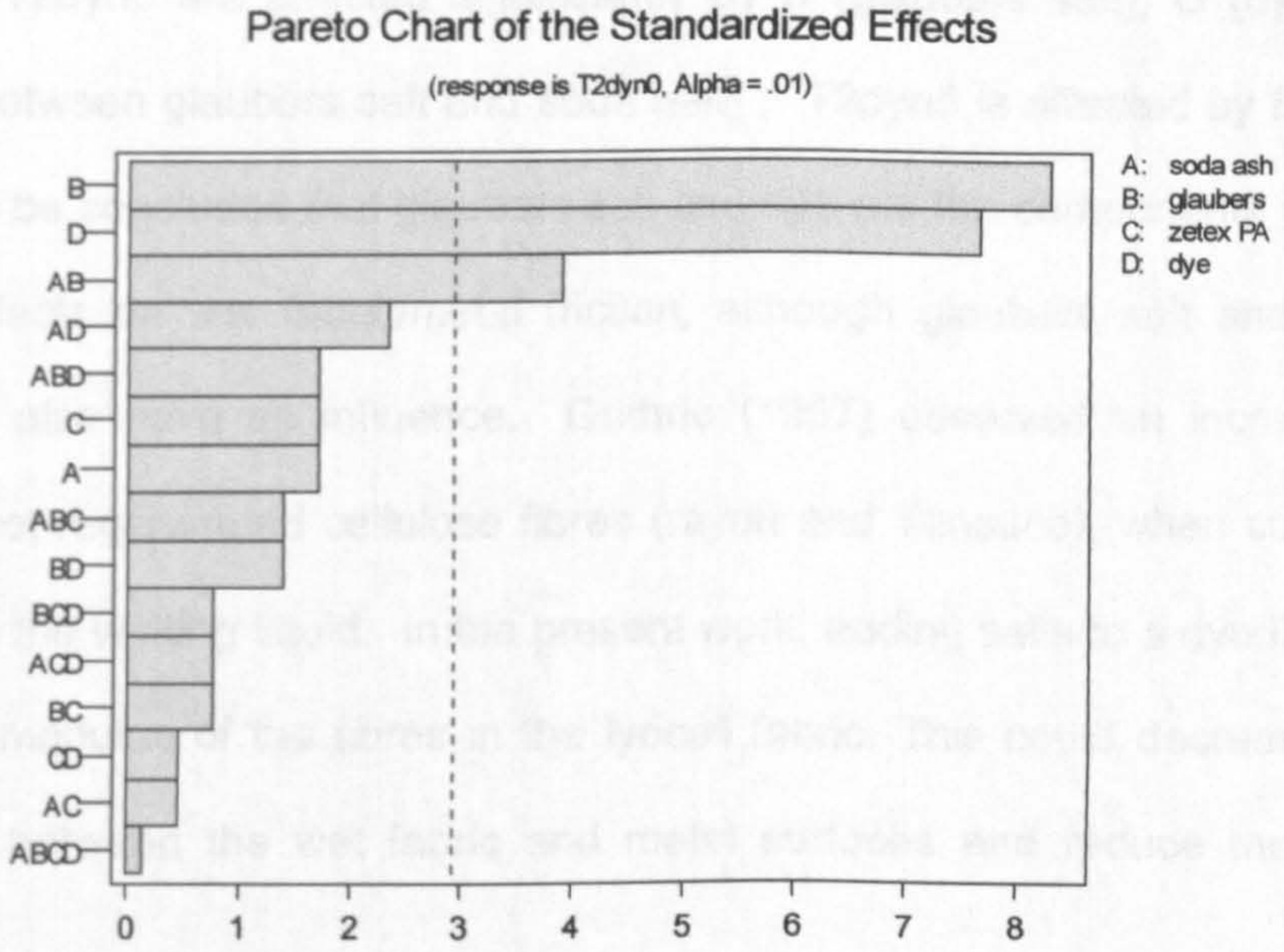


Figure 3.6 Pareto Chart for T2dyn0

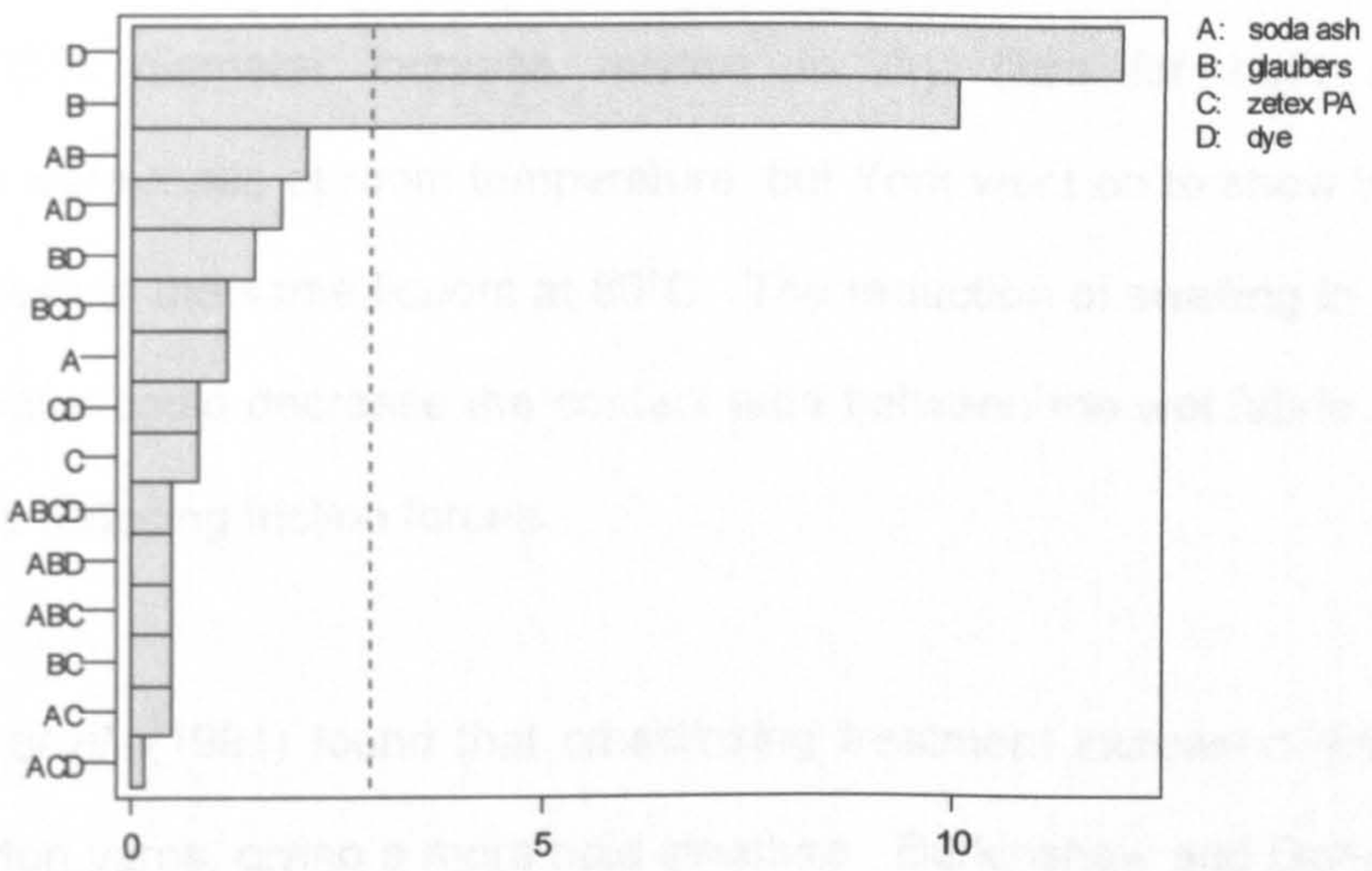


Figure 3.7 Pareto Chart for T2dyn5

T2stat5 and T2dyn0 are affected significantly by B (glaubers salt), D (dye) and AB (interaction between glaubers salt and soda ash) . T2dyn5 is affected by B and D. It can therefore be concluded that glaubers salt and dye are the components which have significant effects on wet fabric/metal friction, although glaubers salt and soda ash together can also have an influence. Guthrie (1957) observed an increase in the modulus of wet regenerated cellulose fibres (rayon and Tenasco), when common salt was added to the wetting liquid. In the present work, adding salts to a dye liquor might increase the modulus of the fibres in the lyocell fabric. This could decrease the true contact area between the wet fabric and metal surfaces and reduce the observed friction force.

York (1997) showed that dye liquor and glaubers salt both reduce the diameter swelling of unconstrained lyocell fibres compared with water. The percentage diameter increase relative to dry fibre was 24% for water, 13% for dye liquor (same composition

as the present work) and 18% for a 55 gl^{-1} solution of soda ash, however a 20 gl^{-1} solution of soda ash and a 3 gl^{-1} solution of Zetex PAL-N also produced lower swelling than water (15% diameter increase relative to dry fibre for both solutions). Measurements were made at room temperature, but York went on to show that lyocell fibres swelled less in the same liquors at 80°C. The reduction of swelling in dye liquor compared to water could decrease the contact area between the wet fabric and metal surfaces, hence reducing friction forces.

Subramaniam *et al.* (1991) found that crosslinking treatment increased the dynamic modulus of cotton yarns, giving a more rigid structure. Burkinshaw and Gandhi (1997) showed that dyed lyocell fabrics exhibited higher wet abrasion resistance than undyed lyocell, however, only Reactive Black 5 and Cibacron Red C-2G gave significant improvements. The increased abrasion resistance was connected to the cross-linking effect and was correlated with dye concentration.

In the present study friction in dye liquor was shown to be reduced relative to friction in water. Cross-linking and increasing the fibre modulus may reduce the contact area between the wet fabric and metal surface, hence reducing the friction and abrasion, but Procion Navy H-ER 150 is unlikely to cross-link lyocell (Snider, 1999). Nicholls (1997) showed that at ambient temperature the extension, tenacity and modulus of lyocell fibres in dye liquor was not dissimilar to the same properties measured in water. A small increase in extension and a minor decrease in modulus were observed but the differences were probably not significant since the 99% confidence intervals of each property overlapped.

Guthrie and Oliver (1952) noted that mock-dyed (i.e. subjected to the dyeing treatment, but without any dye present) viscose yarn showed higher friction forces than dyed yarn prior to rinsing, and suggested that dye on the fibre surface acted as a lubricant.

Overall, the results of the present study are in agreement with the literature findings on the lowering of friction by dyes, although there may be more than one explanation for the effect. It is possible that a number of things happen, i.e. reactions at the fibre surface, a change of wet fibre modulus, and a reduction of swelling, which in combination reduce friction. This is a subject which might be worthy of further investigation.

3.3 FABRIC/METAL ABRASION STUDIES USING SELECTED LUBRICANT SYSTEMS

3.3.1 Introduction

One of the objectives of this work is to attempt to relate friction reduction by lubricants to the level of abrasion damage when wet fabric contacts a metal surface. Controlling abrasion is important during dyeing and finishing of fabrics and unsightly damage can occur on the fabric surface, if precautions are not taken.

3.3.2 Experimental

Navy dyed Lyocell fabric, consisting of Courtaulds lyocell fibres (1.7 dtex) in a Santanderina Q7027, 2/1 twill construction was used. This was the same fabric as was utilised in the wet friction experiments (section 3.2), but it had been dyed to a dark navy shade to enhance contrast of the abrasion damaged regions. The warp face of the fabric was in contact with the steel abrading surface in all tests.

Two methods of abrasion were employed, both are used routinely in fabric quality control assessments. These were the Martindale test and the crock test. Both were adapted for wet fabric testing. It will be shown later that in the initial experiments, the wet Martindale test was not sensitive enough to reveal differences between the lubricants, hence an alternative method was used (i.e. the crock test). This revealed differences in abrasion protection between various lubricants. It is known that there is often little agreement between the results from various standard abrasion tests (Hardarson, 1998). In this work, lubricant performance was quantified using the crock test, which proved appropriate under the experimental conditions employed.

3.3.3 Wet Martindale Testing

3.3.3.1 Experimental

The Martindale abrasion tester is a machine which rubs four fabric samples all at the same time. Gears on the machine change the direction of rubbing after each cycle such that a square region of the test fabric surface is abraded. Normally the test is set up for fabric/fabric abrasion. A wool cloth is placed over a piece of felt and both are held in place by a clamp on the bed of the machine. The test fabric is usually mounted over a separate metal head and held in place by a retainer. The assembly is placed on top of the wool cloth with the two fabrics in contact. The head and test cloth are then moved for the required number of cycles.

In the arrangement employed here, wool cloth was not used and the test fabric was mounted over the felt on the machine base. The moving metal head was uncovered such that fabric/metal abrasion occurred. A 14oz weight was placed on each head assembly. Figure 3.8 is a schematic of the arrangement.

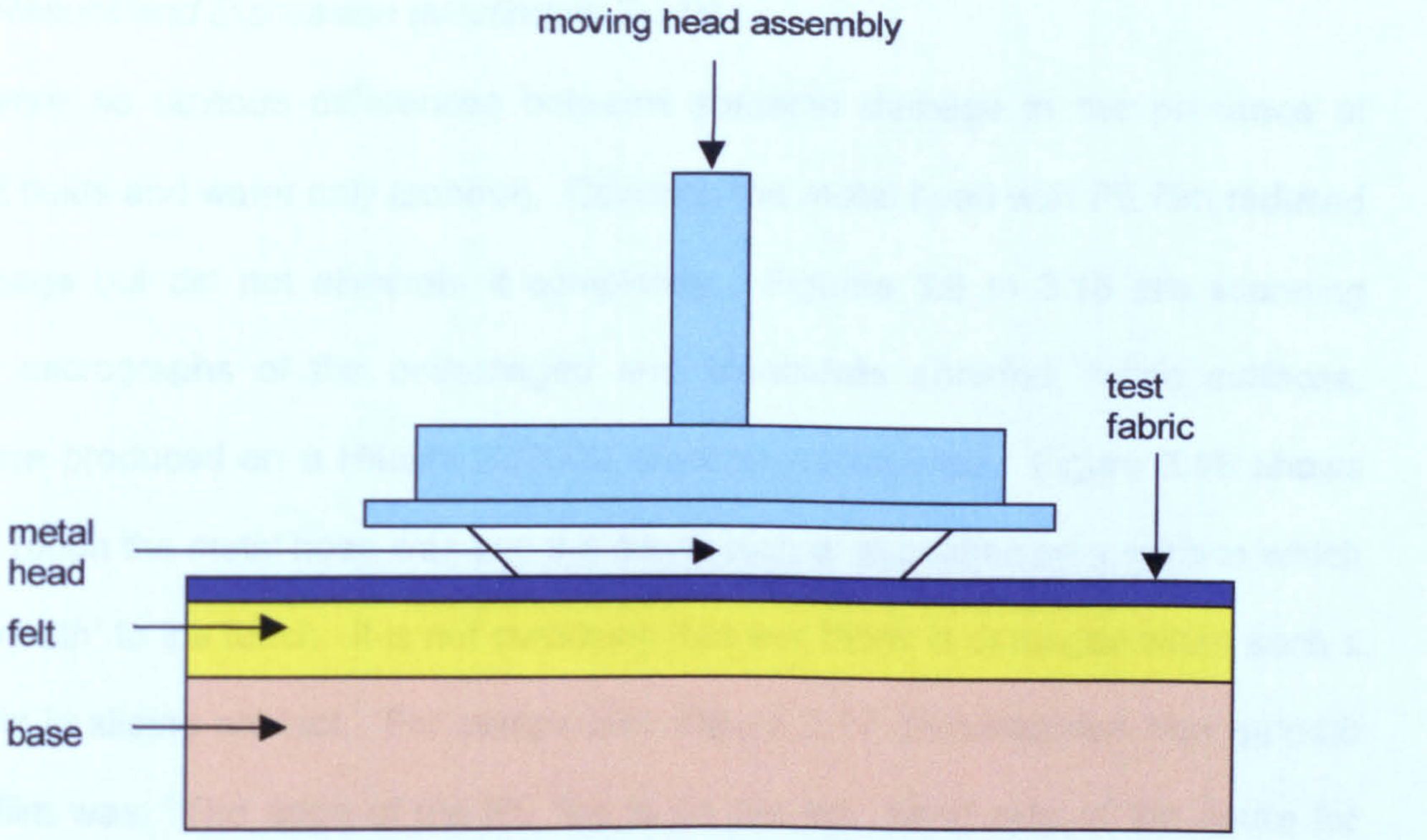


Figure 3.8 Martindale Test Set-Up

Before each group of four tests, the felt was soaked in water for at least 48 hours until wet throughout. Test fabrics were soaked in lubricant fluids for at least 24 hours. Once the test fabrics were in place, the machine was set to run for 1000 cycles. After the tests the fabrics were rinsed thoroughly and dried in an oven. Three replicates were produced for each lubricant.

3.3.3.2 Lubricant Systems Selected

Lubricant systems were selected from those listed in Table 3.1. Although the gums (xanthan, welan and gellan) and bacterial polysaccharide did not reduce wet fabric/metal friction significantly, they were deemed worthy of investigation as novel abrasion reducing agents. This was because of the subjective, slimy feeling that their solutions produce when rubbed between one's fingers and thumb. Water was included as a control and, in a further experiment, the metal abrading surface was covered with poly(ethylene) film to simulate the effect of a polymer coating on the metal.

3.3.3.3 Results and Discussion (Martindale Tests)

There were no obvious differences between abrasion damage in the presence of lubricant fluids and water only (control). Covering the metal head with PE film reduced the damage but did not eliminate it completely. Figures 3.9 to 3.15 are scanning electron micrographs of the undamaged and Martindale abraded, fabric surfaces. They were produced on a Hitachi S3200N electron microscope. Figure 3.16 shows just how rough the metal head was and the distribution of asperities on a surface which feels "smooth" to the touch. It is not surprising that wet fabric is damaged when such a surface is in sliding contact. For comparison Figure 3.17 demonstrates how smooth the PE film was. The edge of the PE film is on the left hand side of the figure for comparison with an otherwise featureless surface.

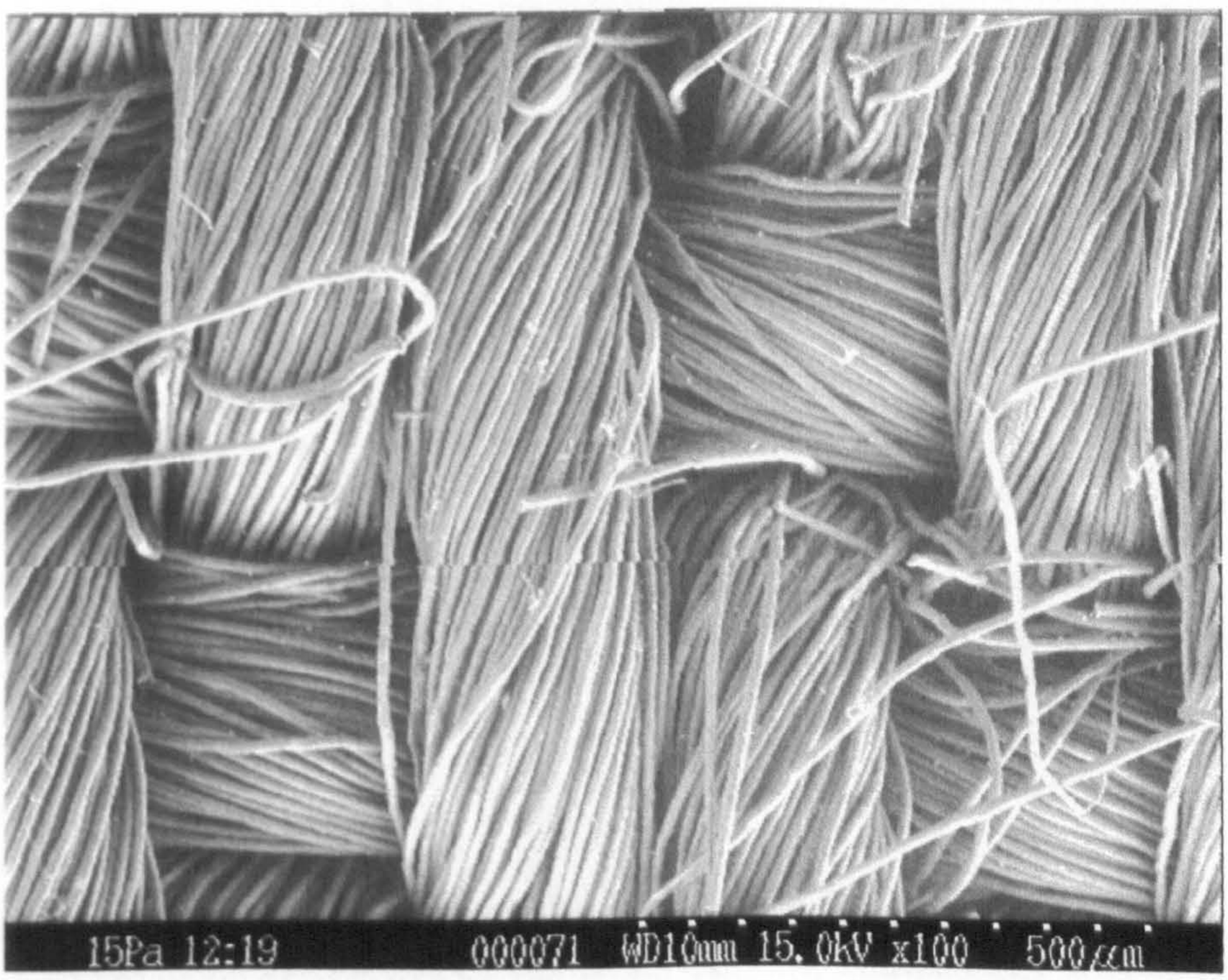


Figure 3.9 Undamaged Fabric Surface

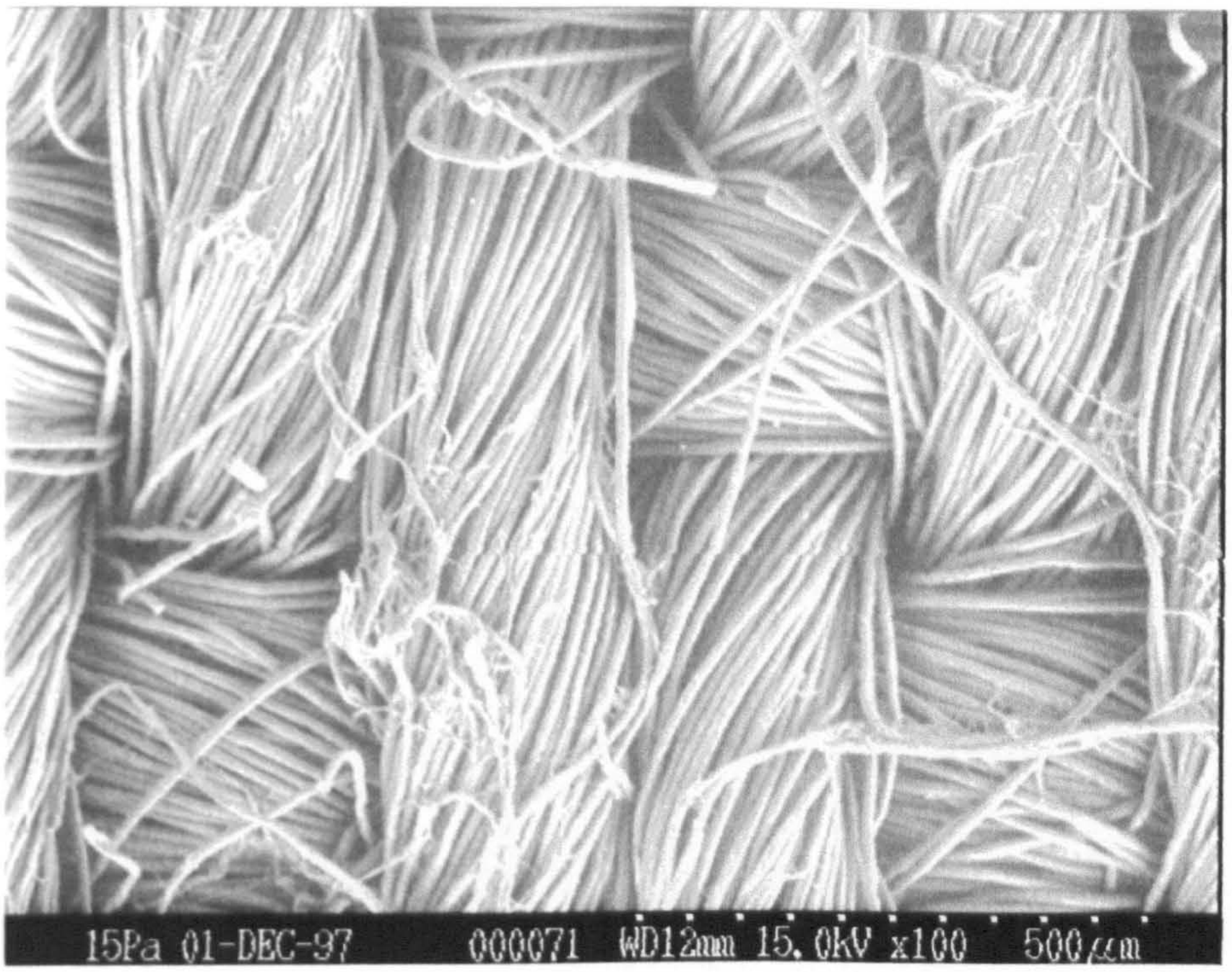


Figure 3.10 Water Control, Martindale Abraded Fabric

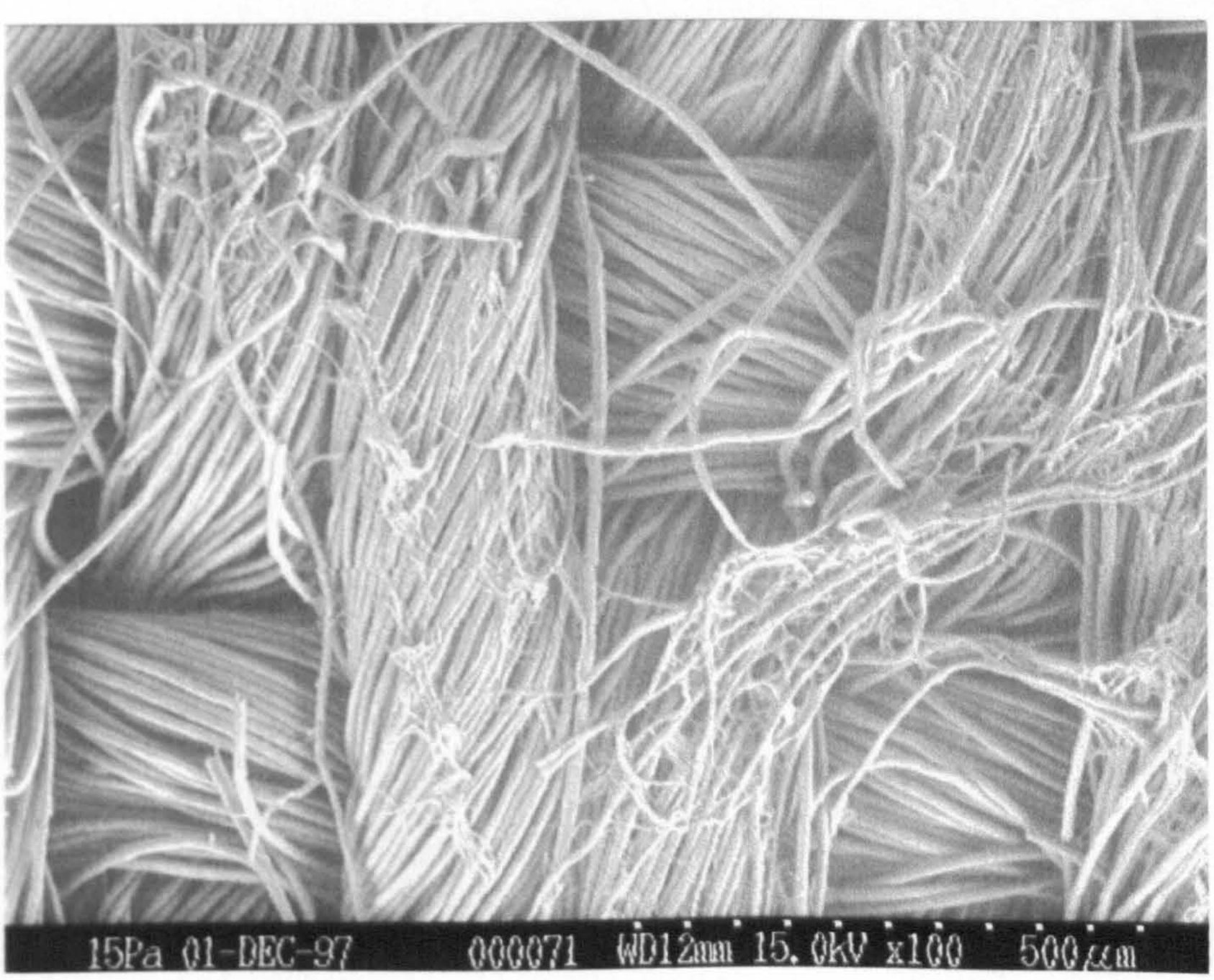


Figure 3.11 Xanthan (5 gl^{-1}), Martindale Abraded Fabric

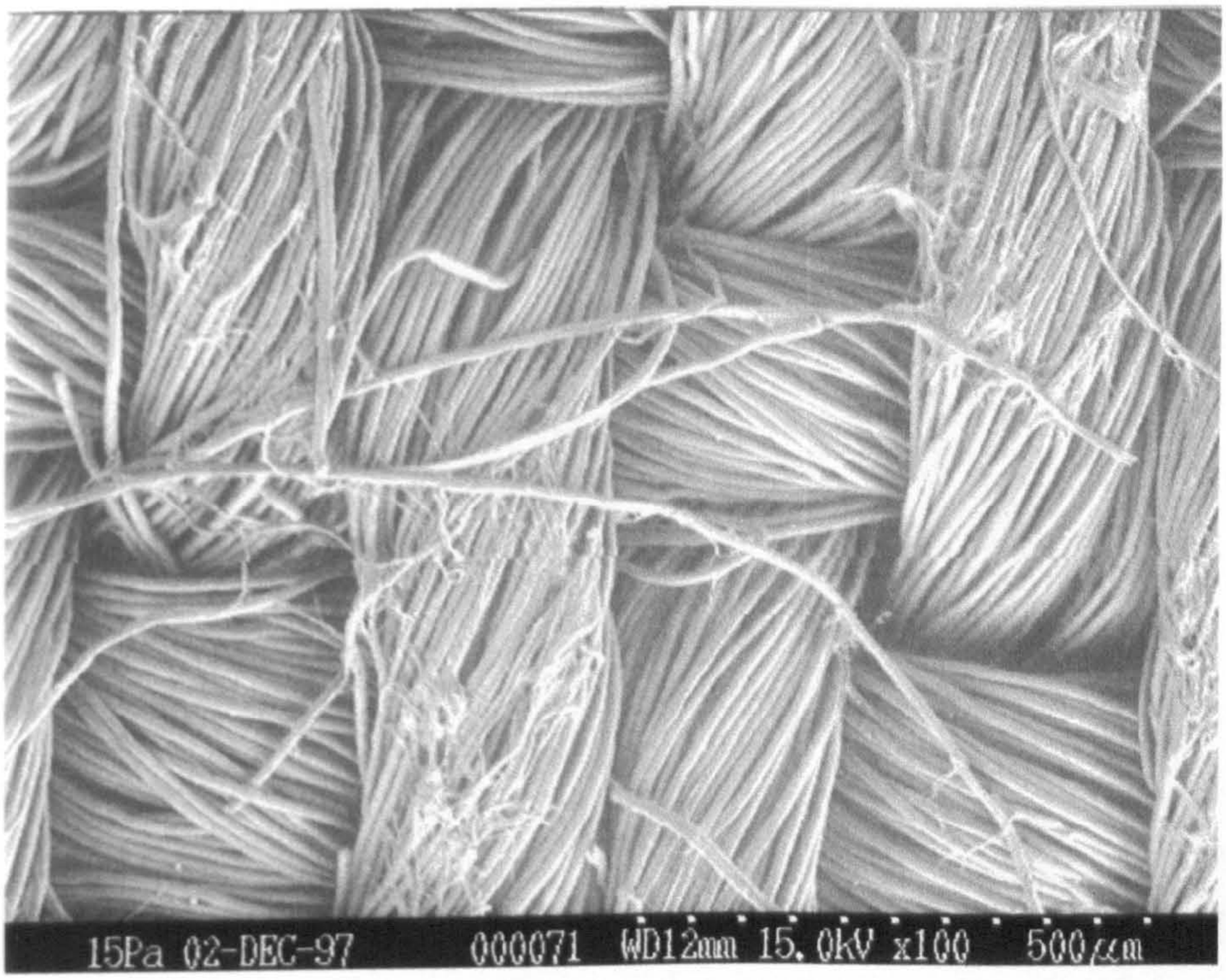


Figure 3.12 Welan (5 gl^{-1}), Martindale Abraded Fabric

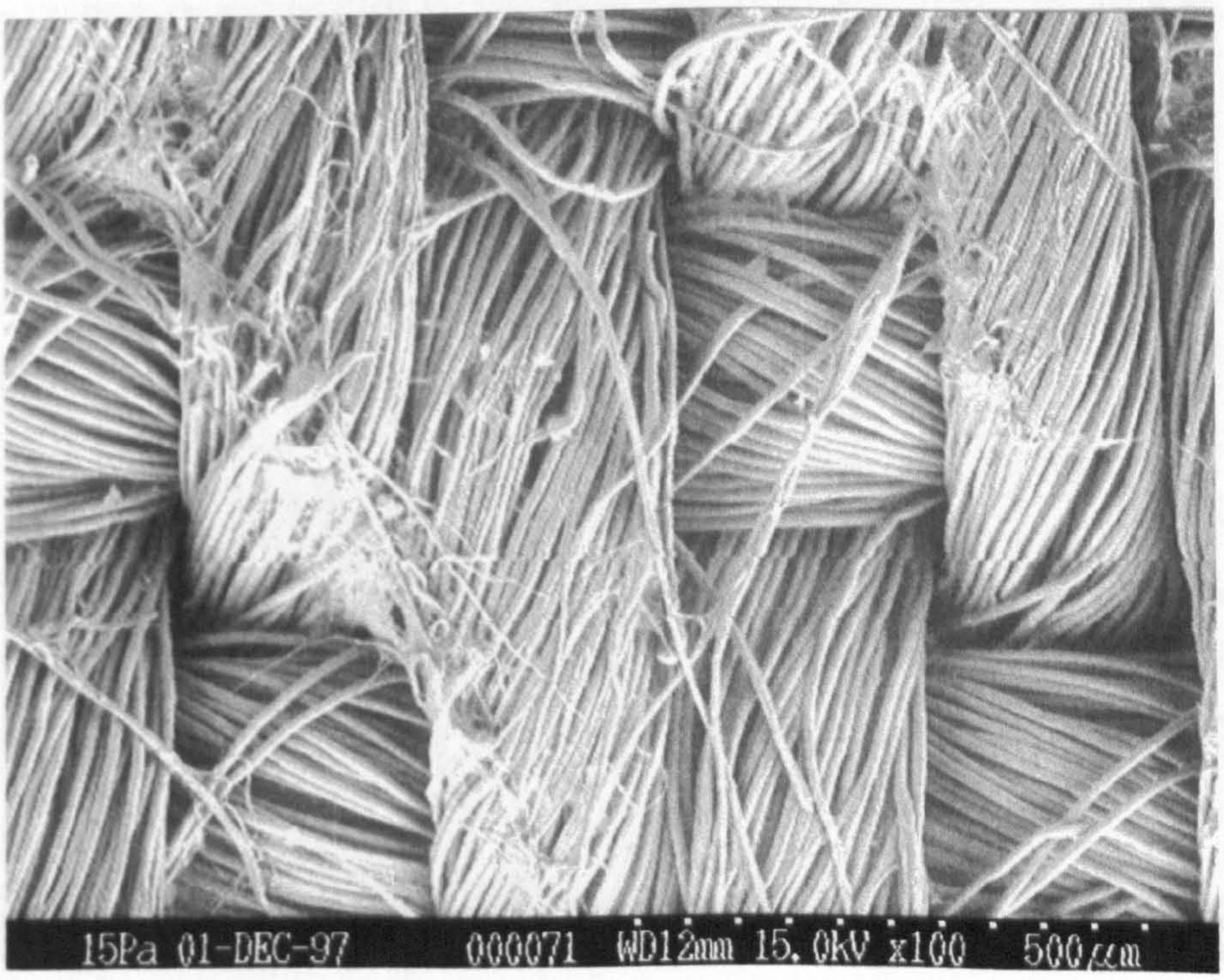


Figure 3.13 Gellan (5 gl^{-1}), Martindale Abraded Fabric

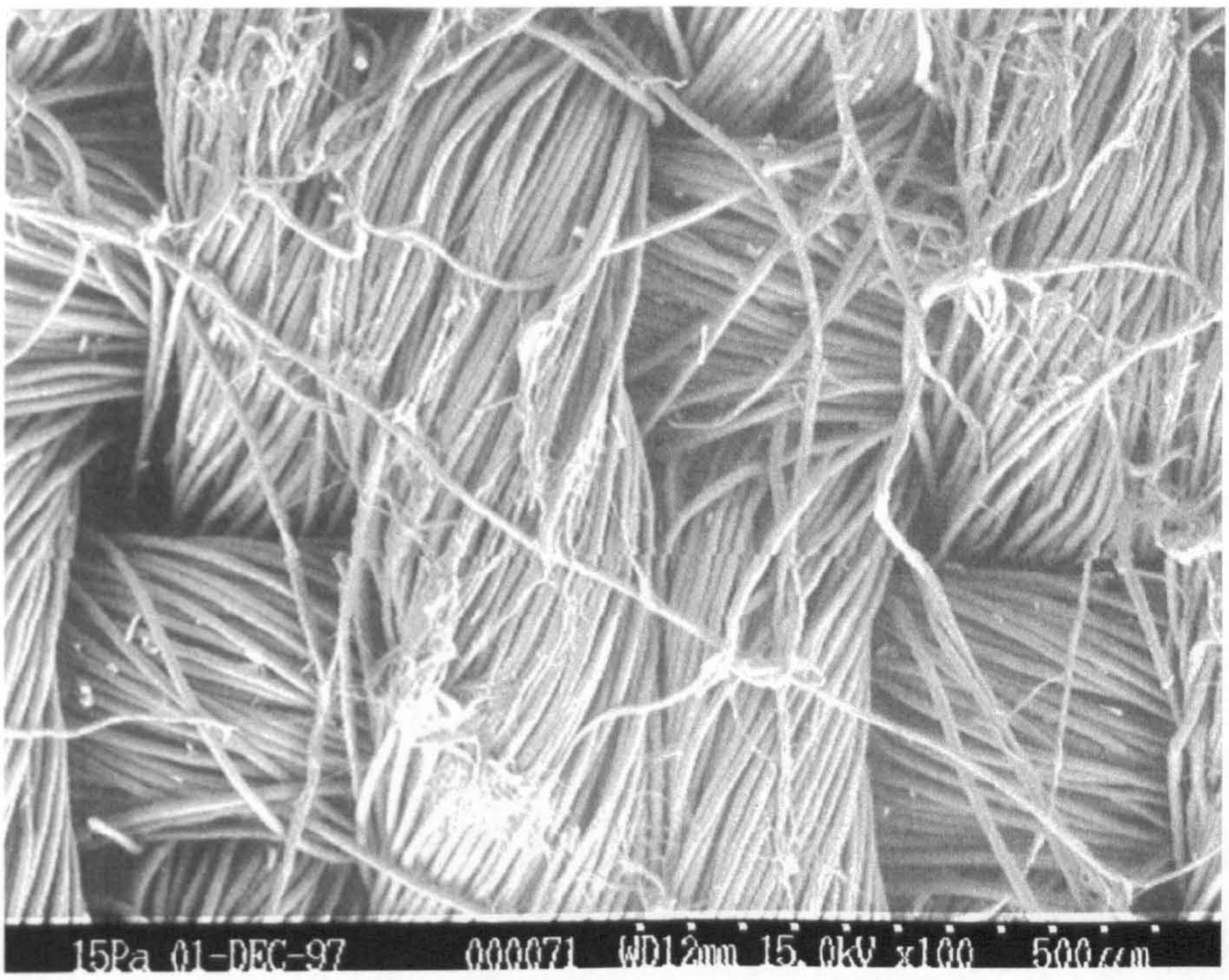


Figure 3.14 Bacterial Polysaccharide (5 gl^{-1}), Martindale Abraded Fabric

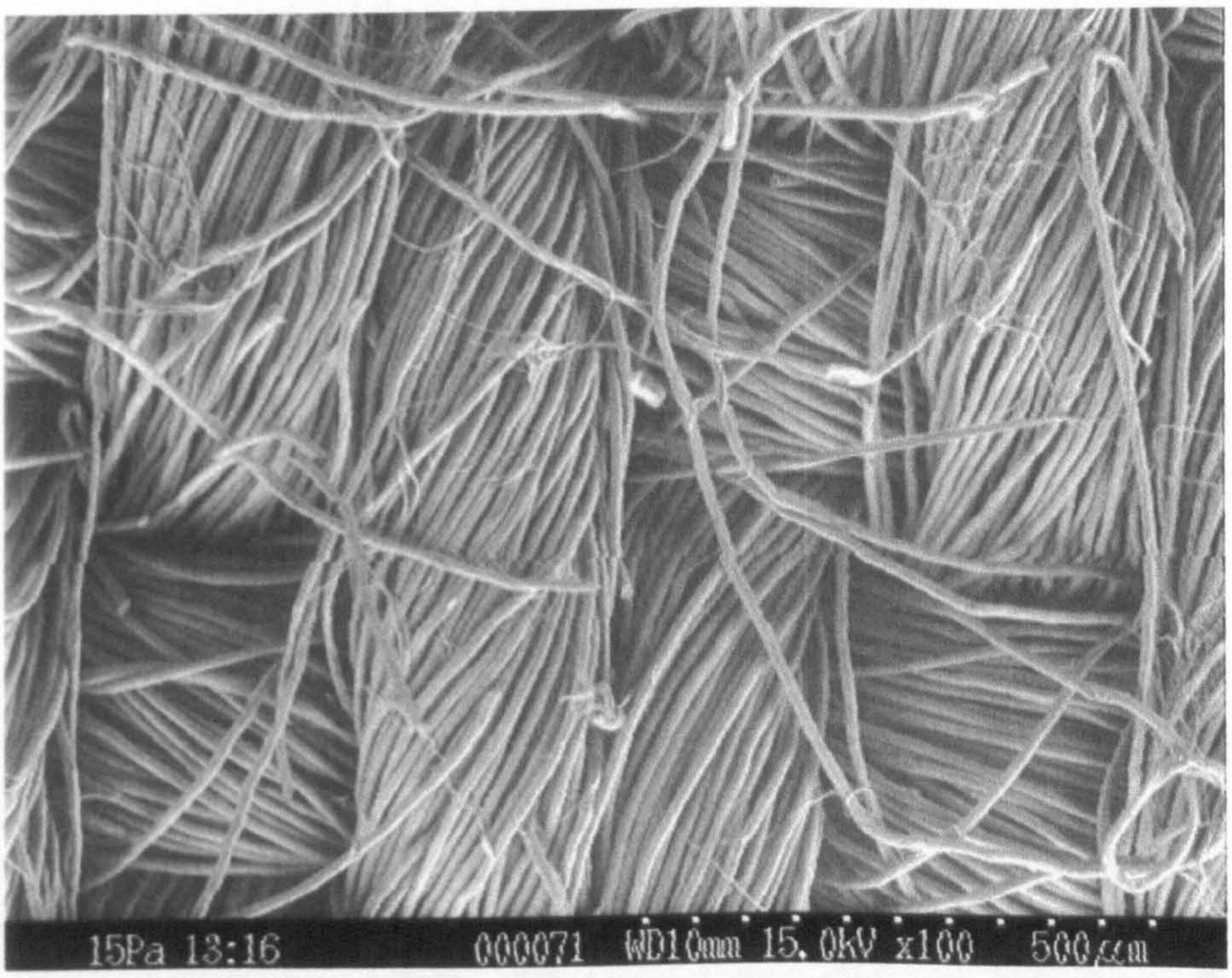


Figure 3.15 PE Film, Martindale Abraded Fabric

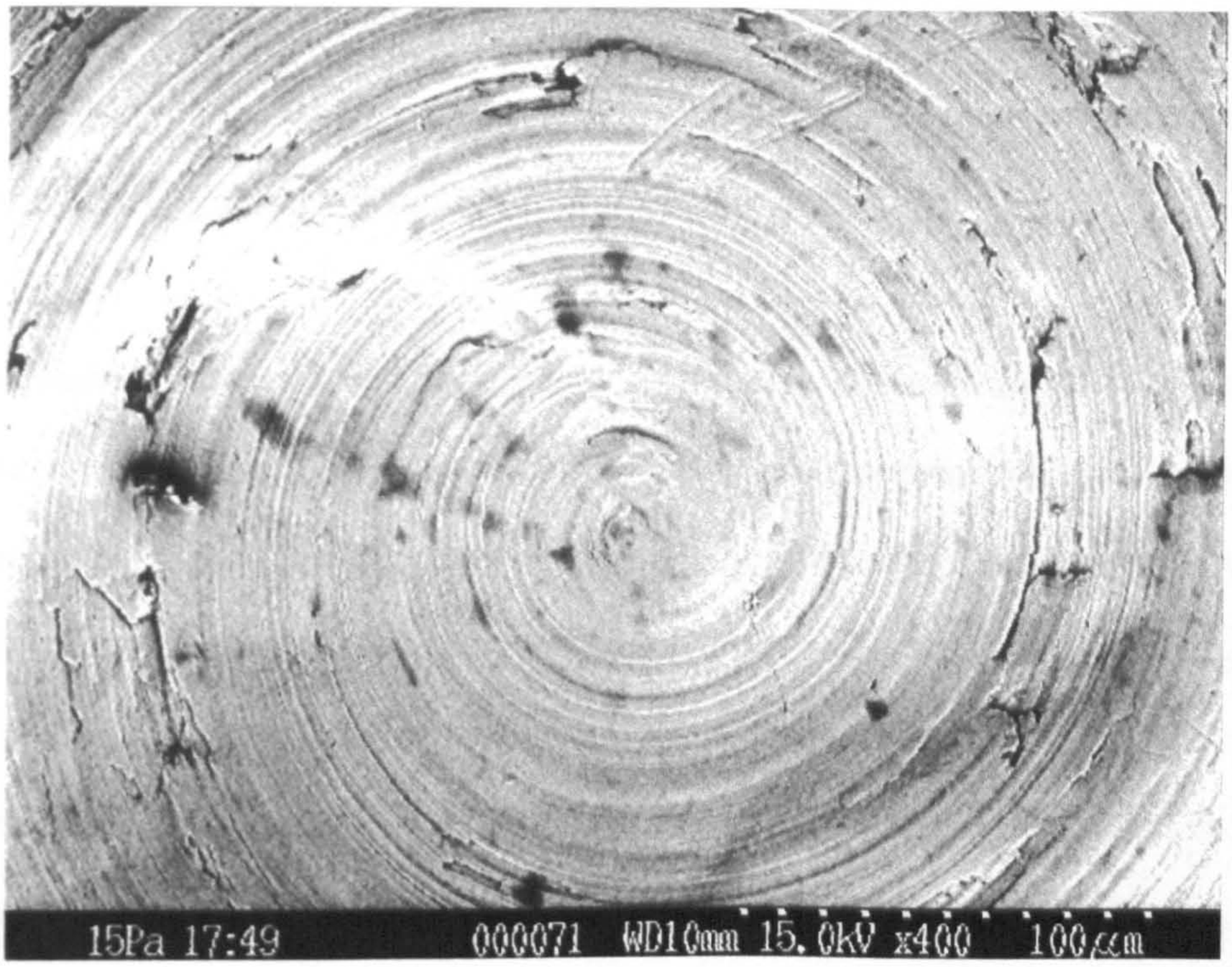


Figure 3.16 Metal Head Used in Martindale Wet Abrasion Tests

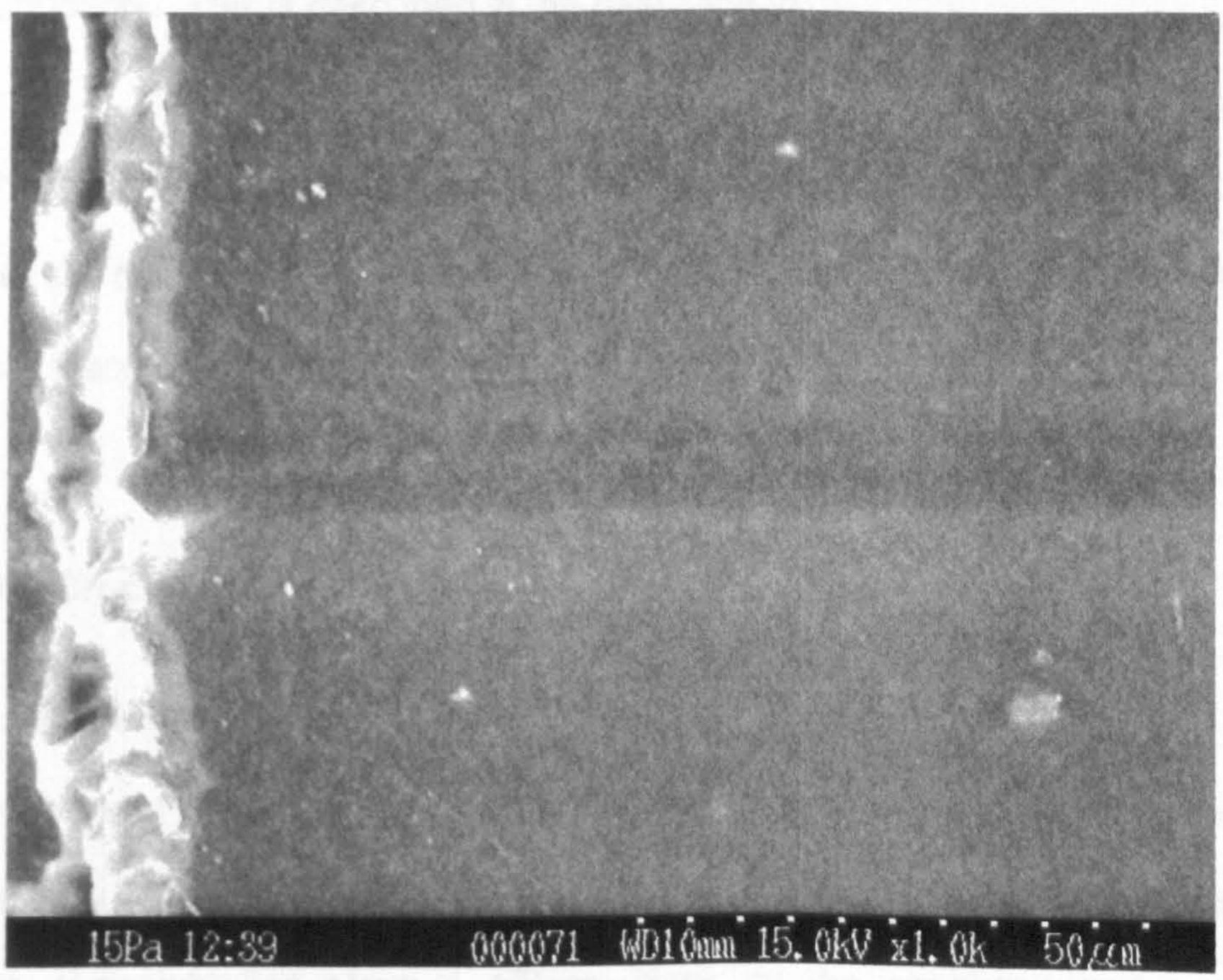


Figure 3.17 PE Film Used to Cover Metal Abrading Head

It can be concluded that the Martindale test was not sensitive enough to reveal differences between the lubricant fluids in abrasion protection, however it did show the reduction in damage when PE film covered the metal head.

The results obtained from particular abrasion tests have been shown to depend on the test method (Hardarson, 1998). In durability tests on sportswear fabrics, differences were seen in the ranked performance of several types of fabric, depending on whether Martindale, Wyzenbeek, Fzd Abrasion (TU Darmstadt), Cambridge Standard for motorcycle clothing, rotary abrasion (Schopper) or Frank Hauser (DIN 53863-2) tests were used. The disagreement in results probably arises from differences in the modes of mechanical action that the fabrics are subjected to in each test.

For the present work, a more sensitive test was required to rank the effects of the various lubricants. This is described in the next section.

It is worth noting that the gellan solution produced a deposit on the dried fabric, which was not easily rinsed off. This had the effect of pasting together fibres and fibrils on the fabric surface and is visible in Figure 3.13.

3.3.4 Wet Crock Testing

3.3.4.1 Experimental

Colour fastness of fabrics to rubbing can be measured with a crocking device. This method usually employs a pin covered with a cotton rubbing fabric, which is moved to and fro in a straight line along a 100mm track on the specimen and exerting a downward force of 9N. The test method is defined in BSEN ISO 105-X12: 1995.

Some simple modifications were made to the test in order to make it suitable for wet fabric/metal abrasion measurements.

The crocking device was supplied by Shirley Developments Ltd., and the bakelite pin incorporated was replaced by a stainless steel pin. This was ground against 120 grit wet or dry paper for 50 cycles of the device, with the abrasive in place of the specimen. The pin was ground before testing each lubricant. Dyed fabrics were soaked for at least 24 hours in the lubricant solution before testing. The wet fabrics were fixed under the ground steel pin and subjected to 50 rubbing cycles, then rinsed and dried. Figure 3.18 demonstrates the test arrangement.

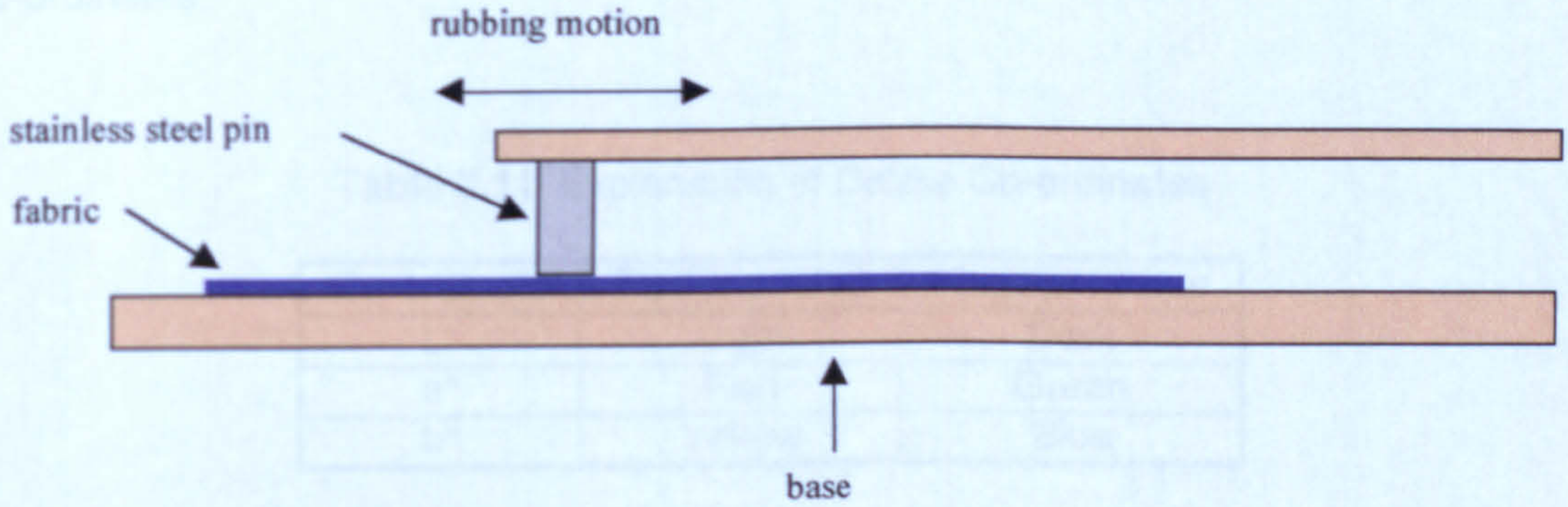


Figure 3.18 Crocking Abrasion Test Set-Up

As in the Martindale tests (see section 3.3.3) xanthan, welan, gellan and bacterial polysaccharide solutions were studied. Again, water was included as a control and, in a further experiment, the steel pin was covered with poly(ethylene) film to simulate the effect of a polymer coating on the metal.

In addition some of the liquids which gave the best friction reduction (see Tables 3.4 to 3.6) were tested. These were Sandoperm MEJ, PEO/PPO and the wax/leomin

dispersion (all in water). Also, solutions of the commercially available lubricants, Perilan VF and Cibafluid C were studied. Solutions in dye liquor were not included, since the damaged areas which appear as lighter could have been dyed during the abrasion experiment, hence masking the damage. Two samples were run with each lubricant and the whole experiment was replicated to produce two complete sets of data.

In order to quantify the damage on each specimen, a Minolta Chroma Meter II, with a D65 light source, was used to record colour space co-ordinates (McLaren, 1987) from damaged and non-damaged regions. Colour space co-ordinates L*, a* and b* indicate the colour of the surface. Table 3.11 shows the colours corresponding to L*, a* and b* co-ordinates.

Table 3.11 Explanation of Colour Co-ordinates

Co-ordinate	Positive value	Negative value
L*	Light	Dark
a*	Red	Green
b*	Yellow	Blue

Where the fabric was damaged, it was lighter in appearance than the non-damaged regions. Hence the colour difference between damaged and non-damaged areas was used to quantify the damage.

Colour difference is calculated from colour co-ordinates according to

$$\Delta E = \sqrt{(\Delta L^{*2}+\Delta a^{*2}+\Delta b^{*2})}$$

where ΔE is the colour difference, and ΔL*, Δa* and Δb* are the differences in each colour co-ordinate between measured regions on the specimen (abraded and reference in this case).

On each crocked fabric panel, three measurements each were made on the abraded and reference (non-abraded) regions, to produce average L*, a* and b* values for the specimen.

3.3.4.2 Results and Discussion (Crock Tests)

The average values of L*, a*, and b* from both regions on each specimen are summarised in Table 3.12.

Table 3.12 Colour Co-ordinates from Crocked Fabrics

Lubricant and sample no.	Region	Replicate	L*	a*	b*
water 1	Ref	1	18.5	3.2	-9.4
		2	18.5	3.4	-9.5
	Abraded	1	22.0	2.9	-12.7
		2	21.0	2.9	-12.1
water 2	Ref	1	18.3	3.2	-9.5
		2	18.6	3.2	-9.5
	Abraded	1	21.6	3.3	-12.4
		2	21.1	2.9	-11.5
wax/leomin 1	Ref	1	18.2	3.3	-9.5
		2	18.6	3.2	-9.6
	Abraded	1	20.5	3.0	-11.0
		2	19.9	3.1	-10.5
wax/leomin 2	Ref	1	18.3	3.3	-9.4
		2	18.5	3.4	-9.6
	Abraded	1	20.8	3.0	-11.2
		2	19.9	2.9	-10.4
PEO/PPO 1	Ref	1	18.2	3.5	-9.6
		2	18.6	3.4	-10.0
	Abraded	1	21.1	3.0	-11.4
		2	20.1	3.2	-10.8
PEO/PPO 2	Ref	1	18.2	3.4	-9.6
		2	18.5	3.5	-9.8
	Abraded	1	20.0	3.3	-10.6
		2	20.2	3.2	-10.7

Table 3.12 Continued

Lubricant and sample no.	Region	Replicate	L*	a*	b*
Sandoperm MEJ 1	Ref	1	18.2	3.5	-9.7
		2	18.0	3.4	-9.4
	Abraded	1	23.5	3.3	-13.9
		2	27.3	2.6	-15.0
Sandoperm MEJ 2	Ref	1	18.3	3.6	-9.6
		2	18.0	3.6	-9.3
	Abraded	1	23.9	3.2	-13.6
		2	26.6	2.5	-14.3
Xanthan 1	Ref	1	18.2	3.3	-8.4
		2	18.6	3.0	-8.7
	Abraded	1	19.6	3.3	-10.3
		2	20.3	2.7	-10.9
Xanthan 2	Ref	1	18.6	3.2	-8.5
		2	18.4	2.9	-8.2
	Abraded	1	19.3	3.2	-10.0
		2	19.4	2.8	-9.8
Welan 1	Ref	1	17.9	3.5	-8.6
		2	18.4	3.1	-8.6
	Abraded	1	19.3	3.2	-10.0
		2	19.7	2.9	-10.3
Welan 2	Ref	1	18.2	3.4	-8.5
		2	18.4	3.0	-8.6
	Abraded	1	19.6	3.4	-10.0
		2	19.5	2.8	-9.9
Gellan 1	Ref	1	18.6	3.6	-9.7
		2	18.4	3.3	-9.4
	Abraded	1	20.3	3.1	-10.9
		2	20.2	3.0	-10.8
Gellan 2	Ref	1	18.4	3.6	-9.7
		2	18.4	3.2	-9.3
	Abraded	1	20.0	3.5	-10.7
		2	19.9	2.8	-10.4
Bacterial PS 1	Ref	1	18.0	3.6	-9.0
		2	18.1	3.2	-8.9
	Abraded	1	19.5	3.4	-10.2
		2	19.6	3.2	-10.3
Bacterial PS 2	Ref	1	18.5	3.6	-9.1
		2	18.3	3.1	-8.8
	Abraded	1	19.4	3.5	-10.2
		2	19.8	3.0	-10.1

Table 3.12 Continued

Lubricant and sample no.	Region	Replicate	L*	a*	b*
PE film 1	Ref	1	18.3	3.7	-9.7
		2	18.5	3.2	-9.5
	Abraded	1	19.6	3.7	-10.4
		2	19.8	3.2	-10.1
PE film 2	Ref	1	18.3	3.7	-9.8
		2	18.5	3.3	-9.5
	Abraded	1	19.8	3.6	-10.6
		2	19.8	3.1	-10.1
Perilan 1	Ref	1	18.5	3.4	-9.8
		2	18.6	3.6	-9.8
	Abraded	1	20.7	3.2	-11.4
		2	20.8	3.2	-11.3
Perilan 2	Ref	1	18.7	3.5	-9.8
		2	18.8	3.5	-9.9
	Abraded	1	21.4	3.3	-12.0
		2	20.6	3.2	-11.7
Cibafluid 1	Ref	1	18.5	3.7	-9.8
		2	18.5	3.7	-9.8
	Abraded	1	20.6	3.4	-12.2
		2	20.5	3.7	-11.5
Cibafluid 2	Ref	1	18.6	3.7	-9.8
		2	18.5	3.9	-9.9
	Abraded	1	21.8	3.5	-12.2
		2	21.5	3.5	-12.3

Figures 3.19 to 3.29 are scanning electron micrographs of the crock abraded fabric surfaces, produced on a Hitachi S3200N electron microscope. The undamaged fabric was illustrated previously in Figure 3.9. Figure 3.30 shows the rough surface of the ground steel pin. The smoothness of the PE film used to cover the steel pin was demonstrated earlier in Figure 3.17.

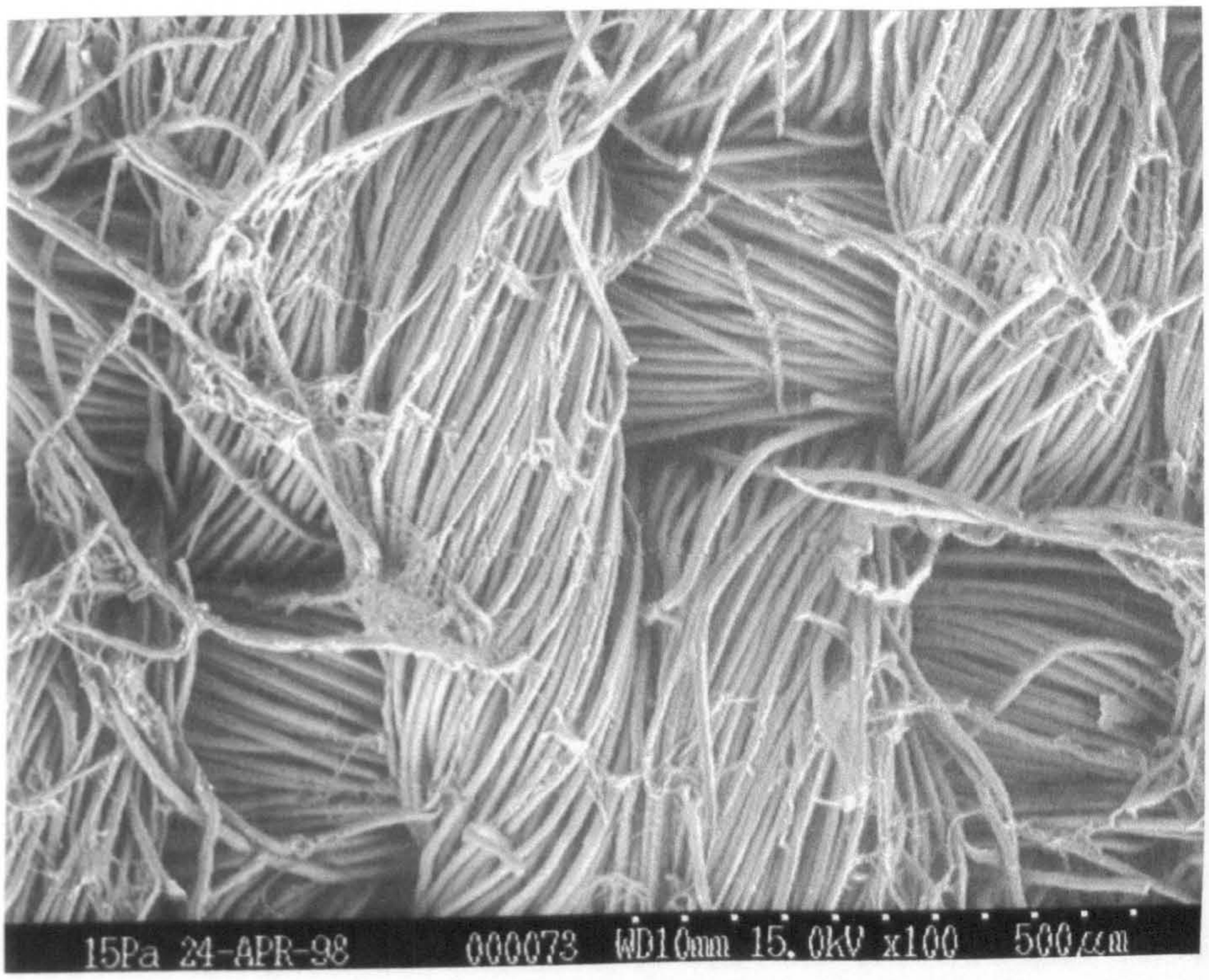


Figure 3.19 Water Control, Crocked Fabric

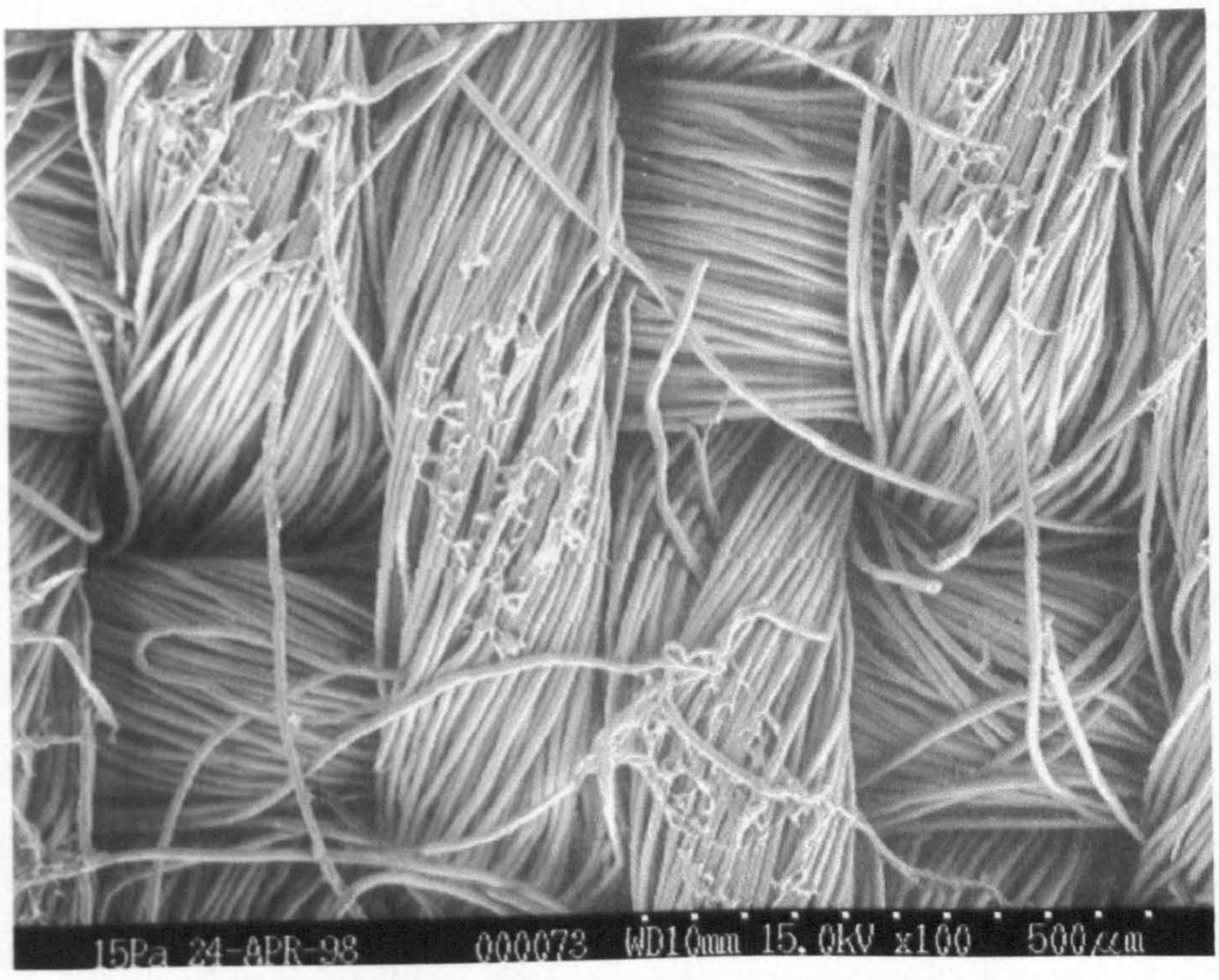


Figure 3.20 Xanthan (5 gl^{-1}) Crocked Fabric

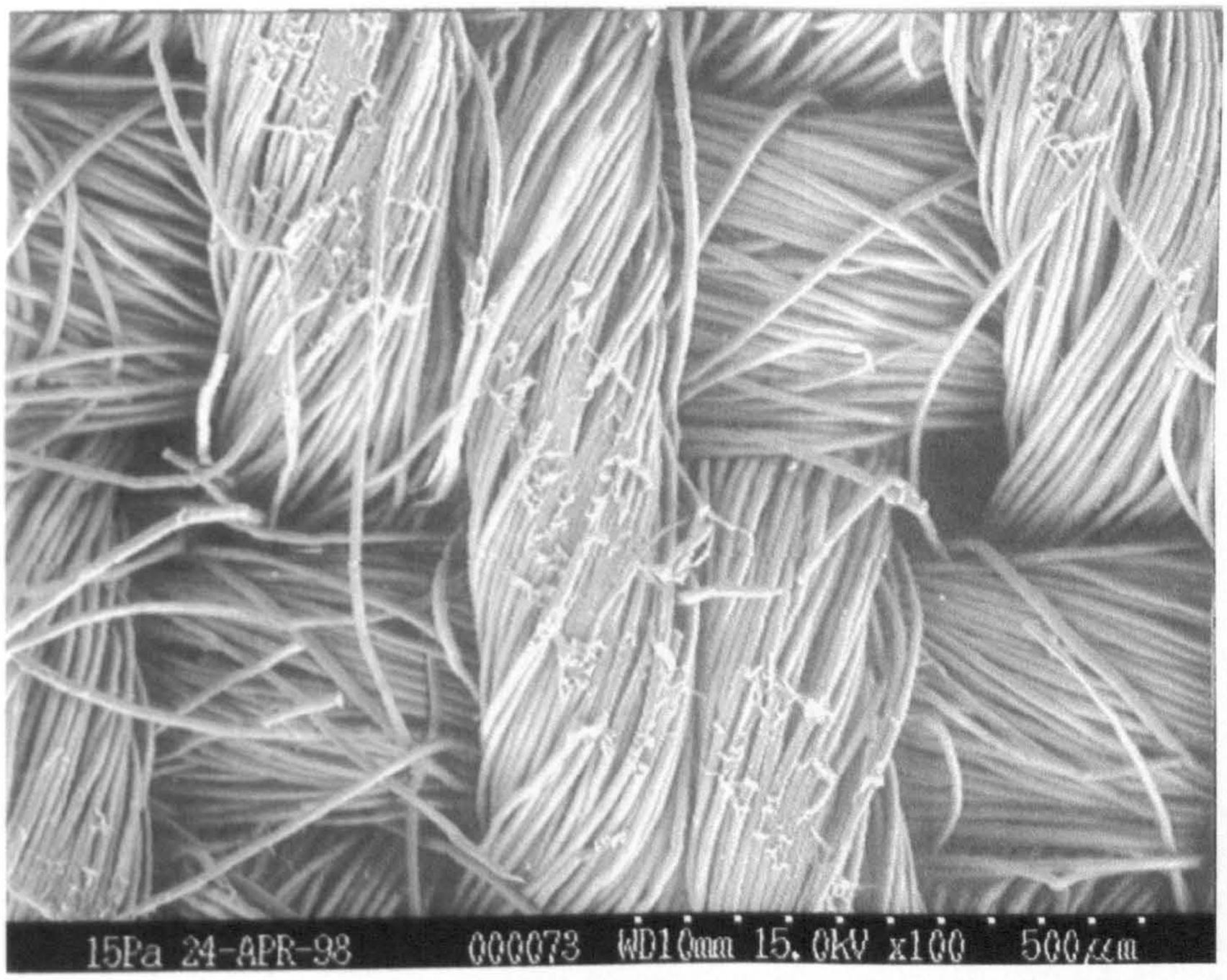


Figure 3.21 Welan (5 gl^{-1}) Crocked Fabric

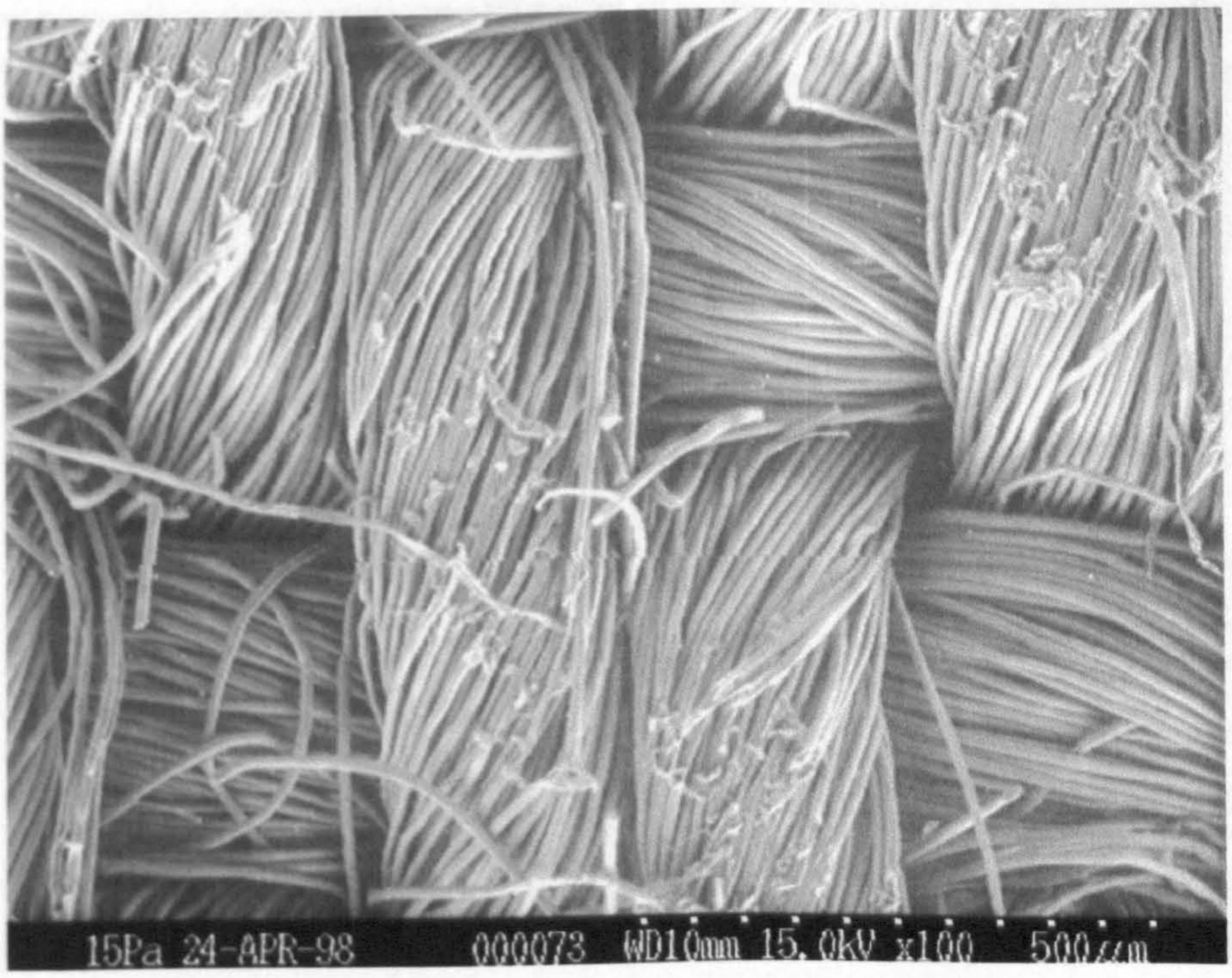


Figure 3.22 Gellan (5 gl^{-1}) Crocked Fabric

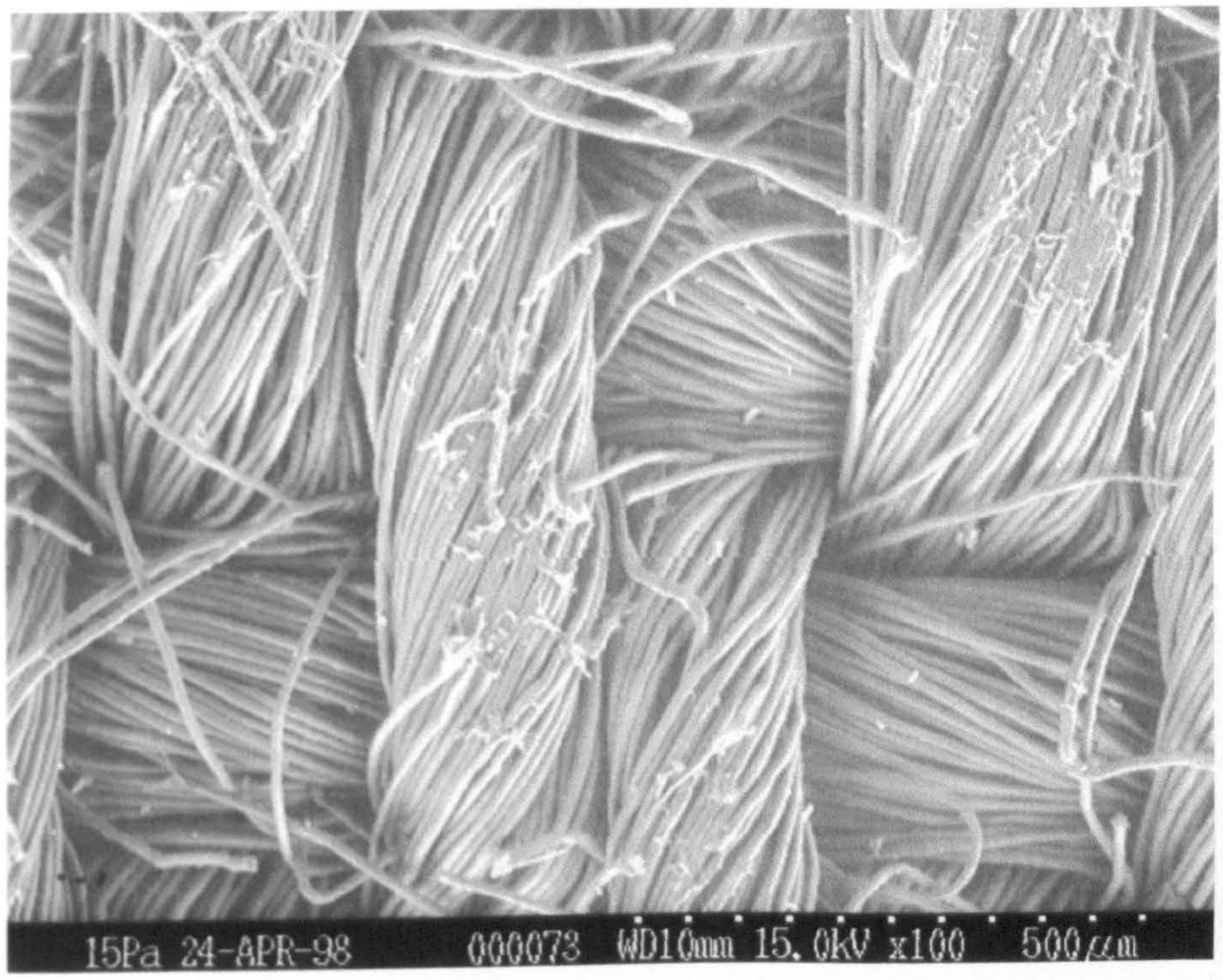


Figure 3.23 Bacterial Polysaccharide (5 gl^{-1}) Crocked Fabric

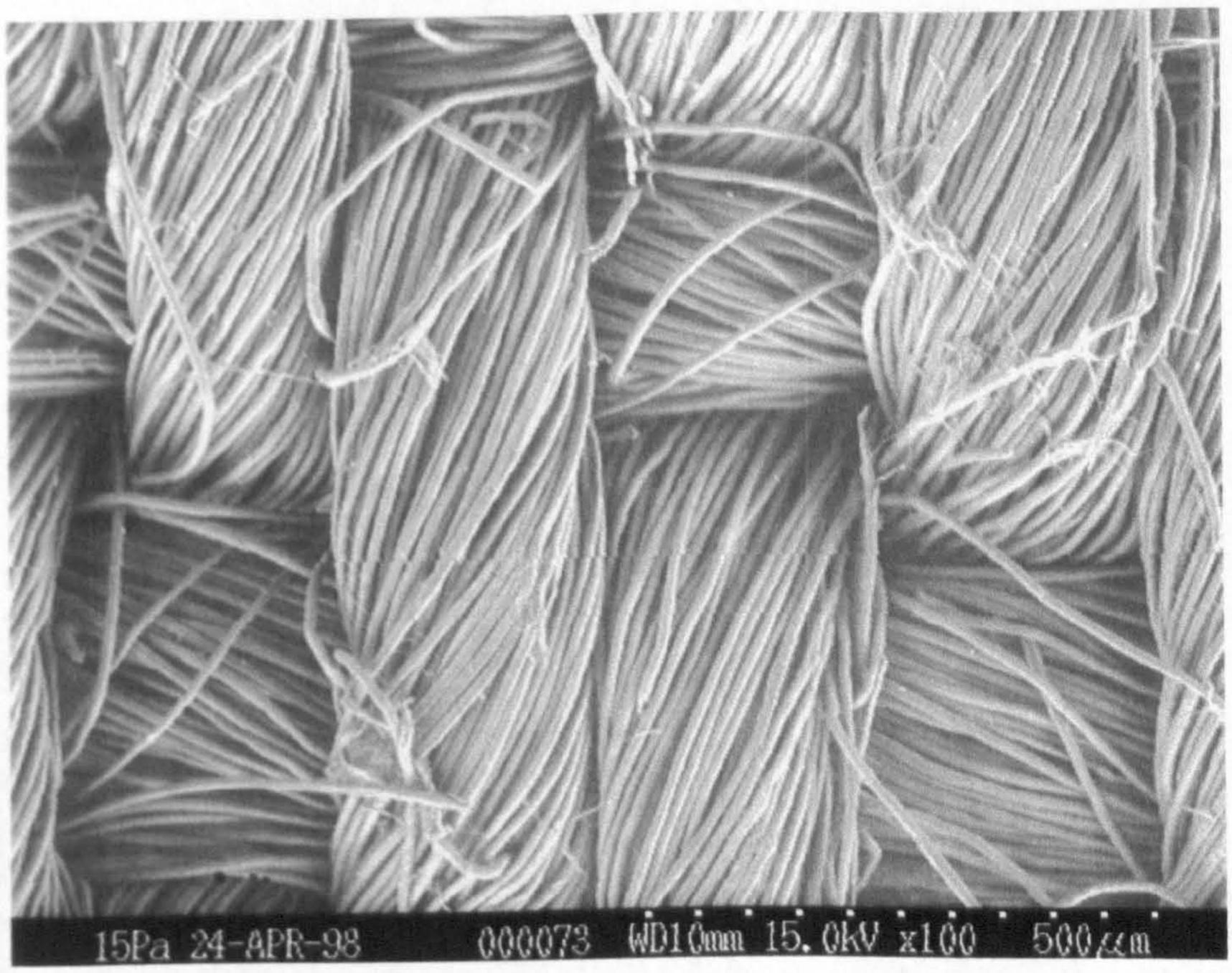


Figure 3.24 PE Film & Water Crocked Fabric

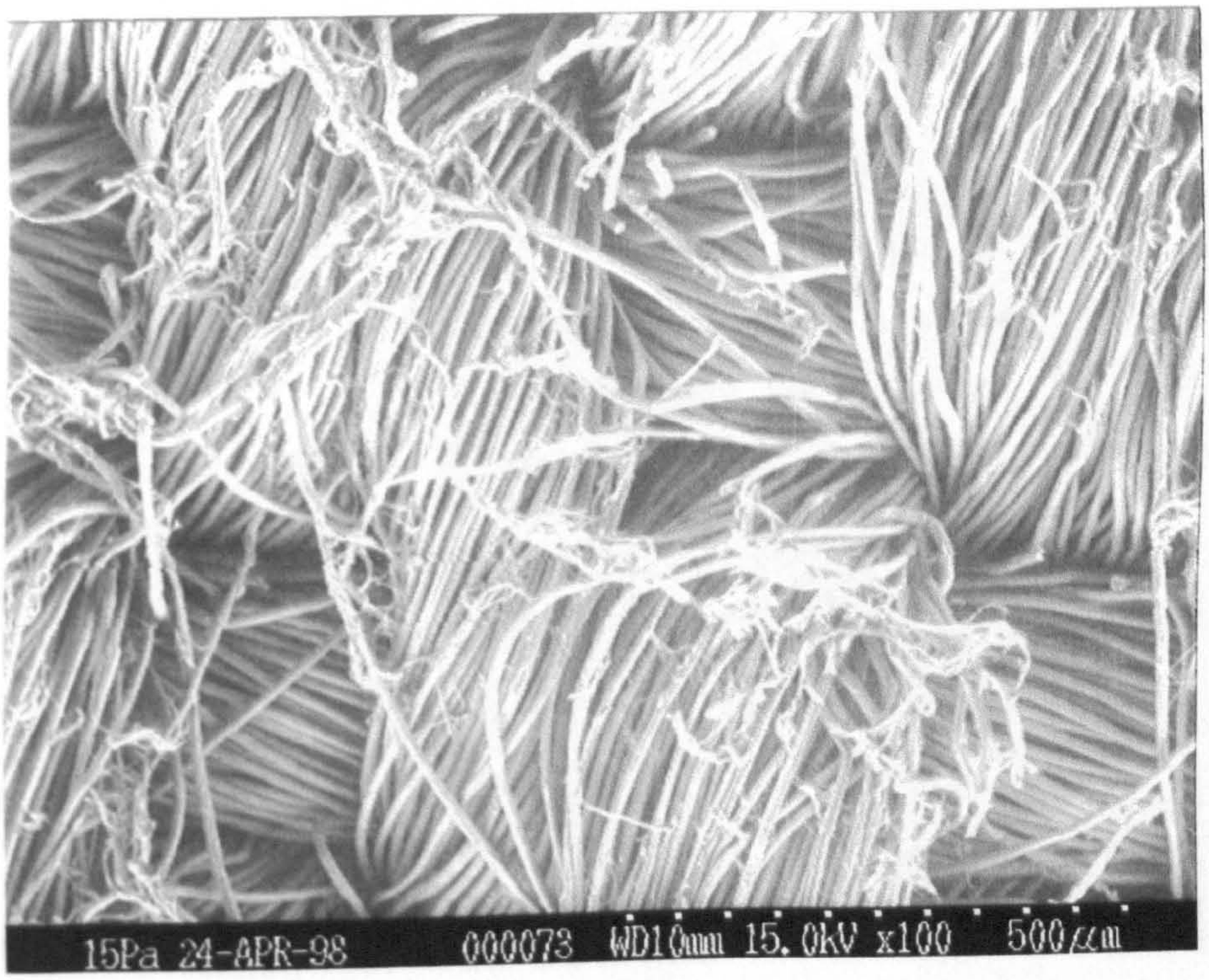


Figure 3.25 Sandoperm MEJ (5 gl^{-1}) Crocked Fabric

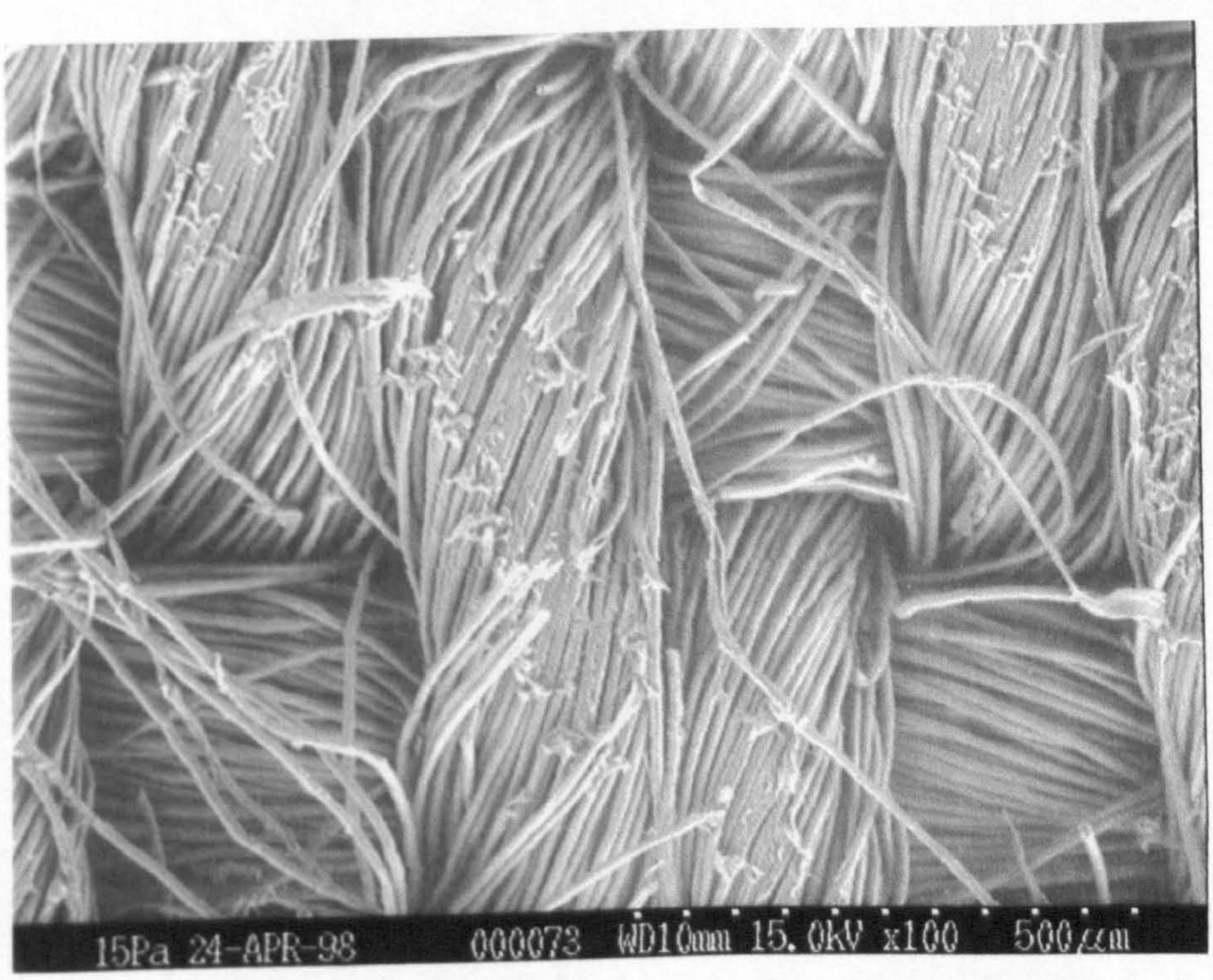


Figure 3.26 PEO/PPO (5 gl^{-1}) Crocked Fabric

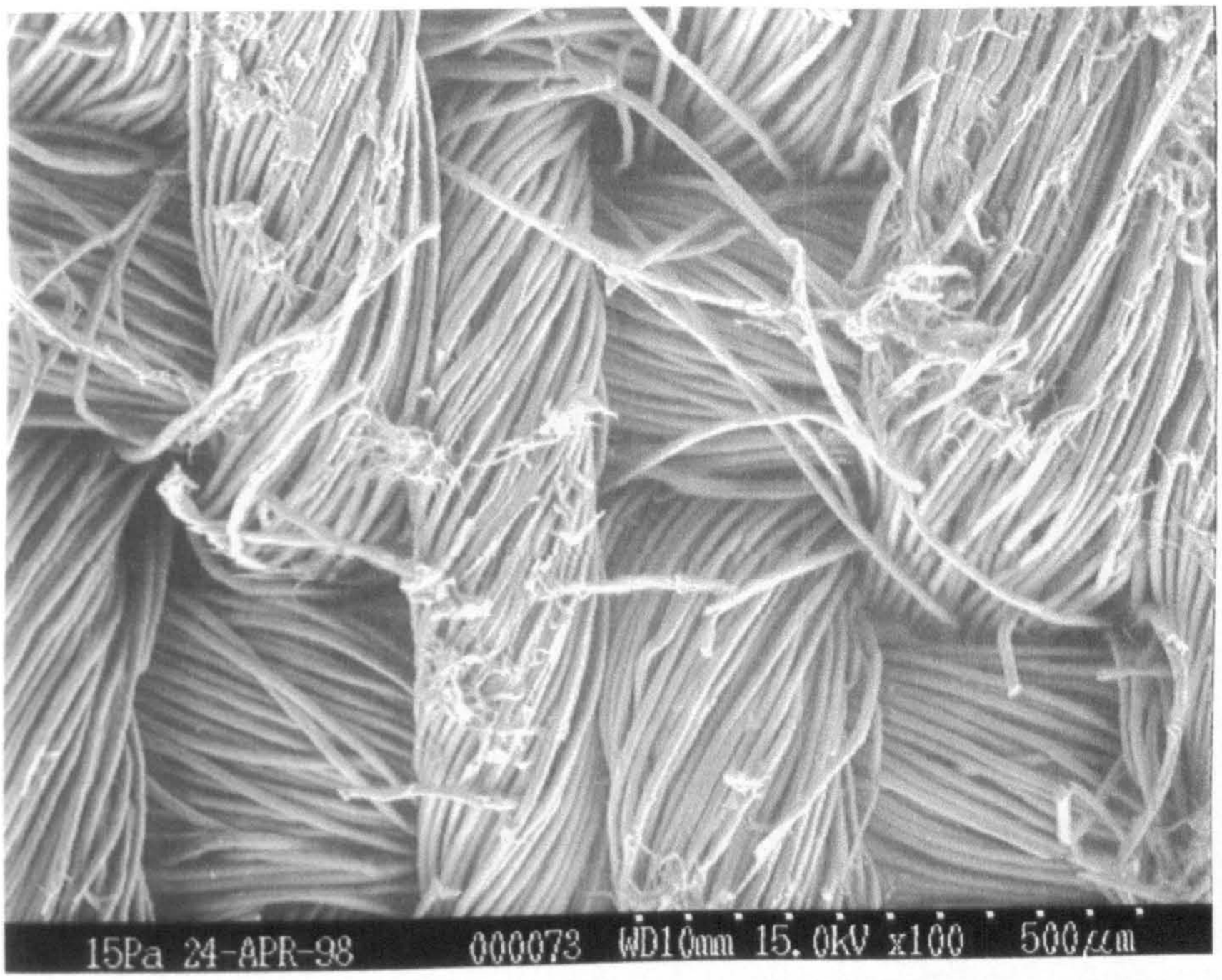


Figure 3.27 Wax/Leomin (2 gl^{-1}/0.5 gl^{-1}) Crocked Fabric

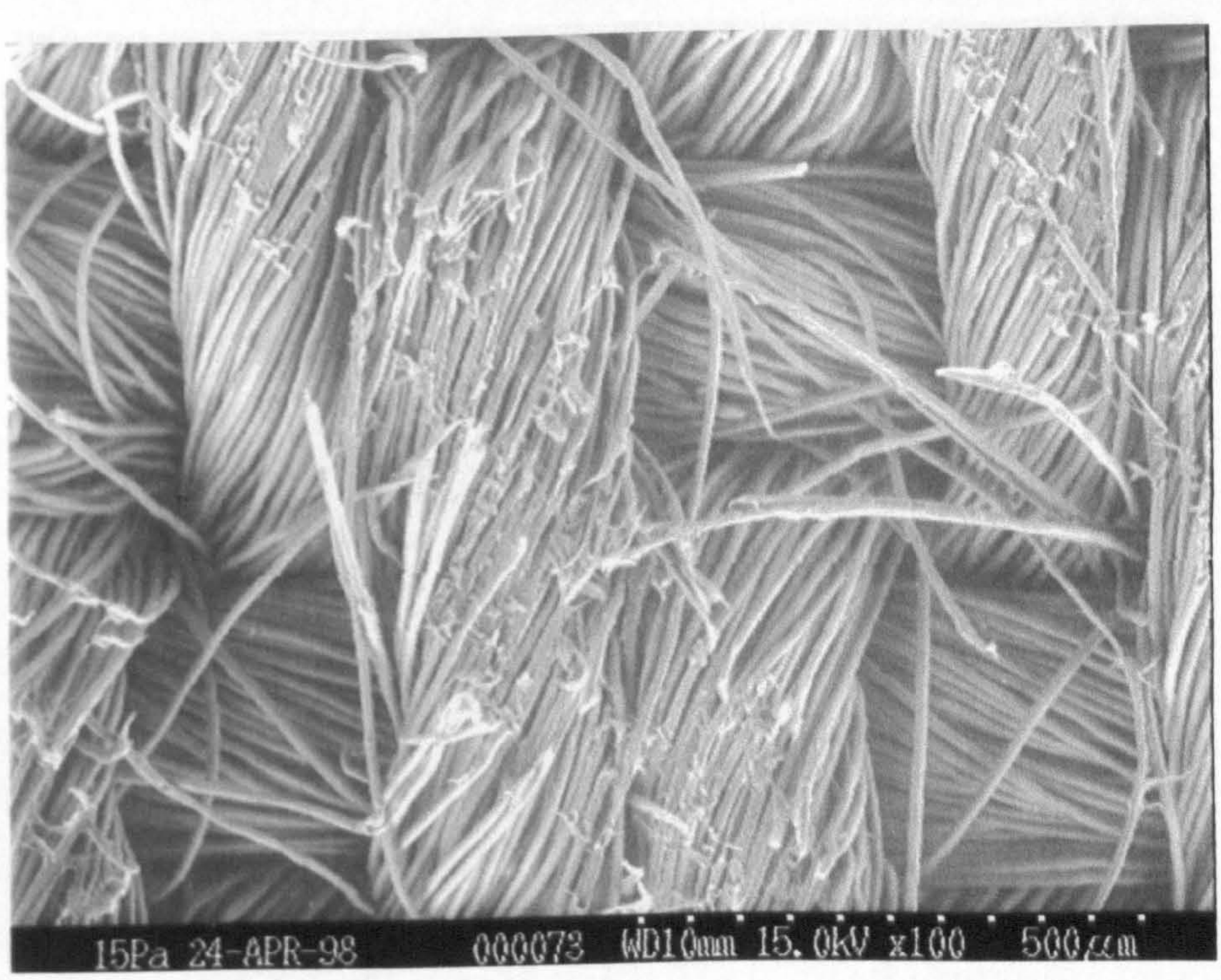


Figure 3.28 Perilan VF (5 gl^{-1}) Crocked Fabric

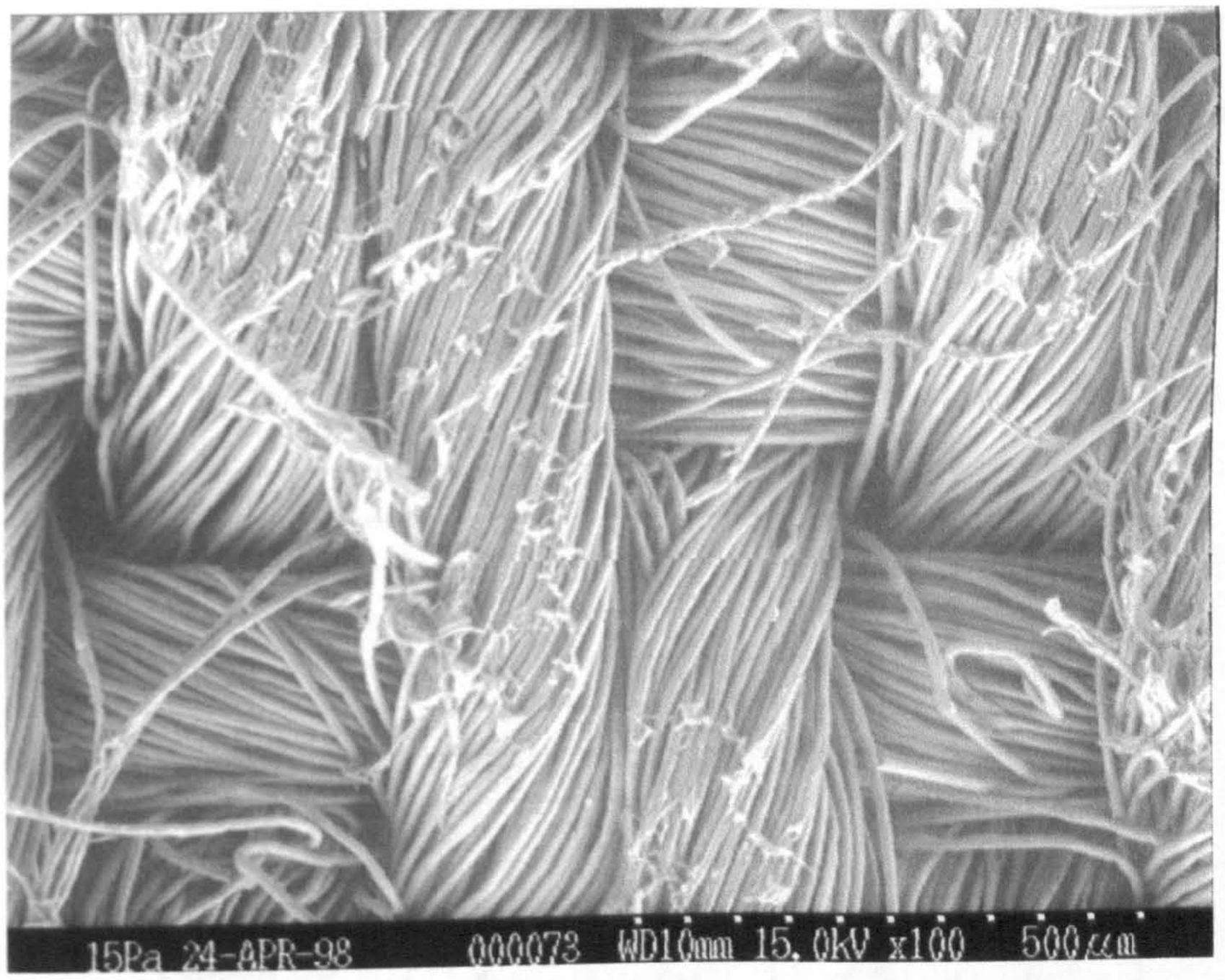


Figure 3.29 Cibafluid C (5 gl^{-1}) Crocked Fabric

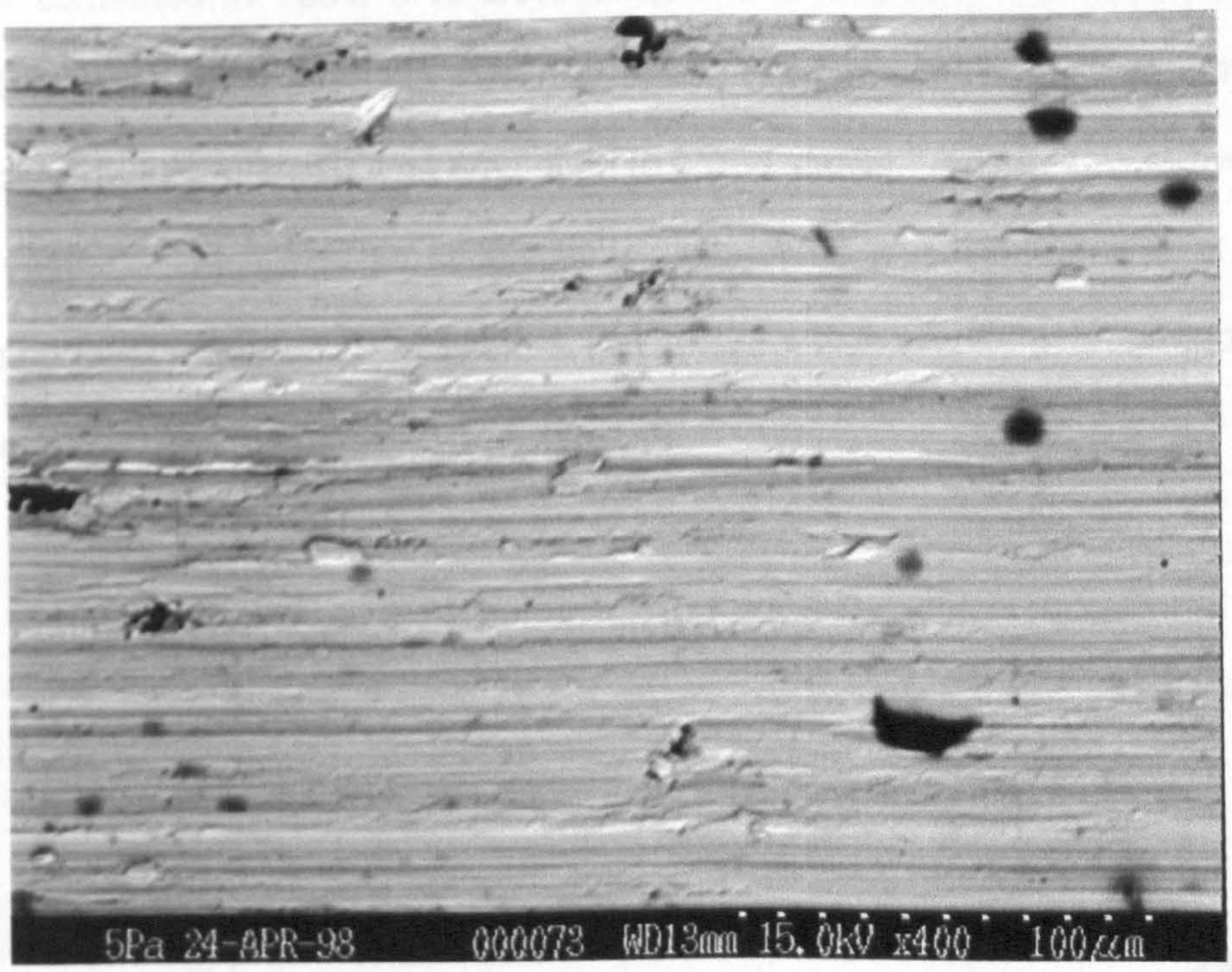


Figure 3.30 Surface of Steel Crocking Pin After Grinding (120 grit)

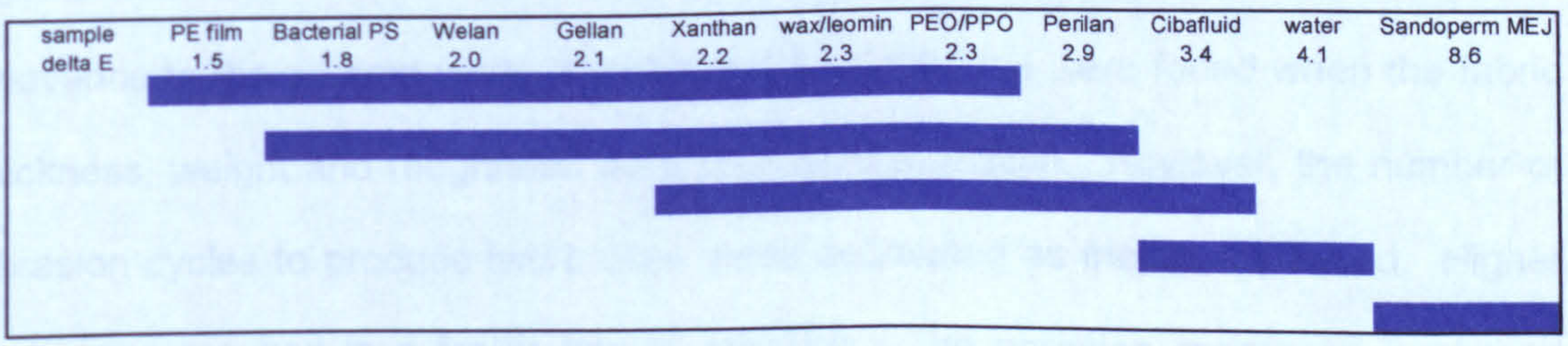
The colour co-ordinates from Table 3.12 were used to calculate the colour difference for each fabric sample. This produced four delta E results for each lubricant (from two samples with two replicates). The delta E values are shown in Table 3.13.

Table 3.13 Delta E Values for Fabric Abraded in Various Lubricants

Liquid	result #1	result #2	result #3	result #4
Water	4.9	3.7	4.4	3.2
Wax/leomin	2.8	1.6	3.1	1.7
PEO/PPO	3.4	1.8	2.1	1.9
Sandoperm MEJ	6.7	10.9	6.9	10.0
Xanthan	2.3	2.8	1.7	1.9
Welan	2.0	2.2	2.0	1.7
Gellan	2.1	2.3	1.9	1.9
Bacterial PS	1.9	2.0	1.4	2.0
PE film	1.5	1.5	1.7	1.4
Perilan VF	2.7	2.7	3.4	2.6
Cibafluid C	3.2	2.7	3.9	3.9

The data contained in Table 3.13 were subjected to analysis of variance (ANOVA) tests. Using the output of the ANOVA tests, Duncan's new multiple range test (Statistics for Industry, 1996) was employed to group similar lubricants, in terms of their delta E values. The test also shows which lubricants give differences at the 5% significance level. The bands in Table 3.14 indicate which results overlap and are not significantly different.

Table 3.14 Grouping of Delta E Results



Clearly, this test distinguishes the performance of the lubricants and shows which conditions give a reduction in abrasion damage, compared to the water control. The least damage occurred when the steel pin was covered with poly(ethylene) film. This suggests that coating metal machine surfaces with a low friction polymer might be the best way to reduce damage to fabrics when dyeing and finishing, although the bacterial polysaccharide, the gums (xanthan, welan and gellan), the wax dispersion and PEO/PPO solution also performed well. Considering the commercial lubricants, Perilan VF provided some protection but Cibafluid C was not significantly different to the water (control). Surprisingly, Sandoperm MEJ increased abrasion damage. Sandoperm gave some of the lowest wet fabric/metal friction coefficients, so how can it increase abrasion? A plausible mechanism is that the low friction produced by the siloxane allows fibres in the yarns to slide out easily and become loose at one end, forming surface hairs, whilst still anchored at the other end. The hairs, which are uppermost on the fabric surface become most prone to damage since they are the first point of contact with the sliding surface. The surface area of the hairs is small compared to the rest of the fabric, so when the sliding load is applied, greater pressures are generated than if the fabric weave were to bear the load. This might result in increased damage.

Amirbayat and Cooke (1989) studied the friction and abrasion of various textile fabrics against metal. The work was done with dry fabrics but their results have some relevance to the present work. No significant correlations were found when the fabric thickness, weight and roughness were compared to friction. However, the number of abrasion cycles to produce two broken yarns decreased as friction increased. Higher resistance resulted in a faster rate of abrasion. The abrasion resistance increased when the weight and thickness of the fabric was increased.

In the present work, it appears that a simple relationship between friction and abrasion reduction might not exist, if other factors such as fabric hairiness are involved. Average wet friction forces (T2stat5, T2dyn0 and T2dyn5) were correlated against average delta E values. The results are shown in Table 3.15.

Table 3.15 Correlation Coefficients: Friction and Abrasion

	deltaE	*T2stat5*	*T2dyn0*	*T2dyn5*
deltaE	1.000			
T2stat5	-0.353	1.000		
T2dyn0	-0.487	0.876	1.000	
T2dyn5	-0.373	0.724	0.808	1.000

With 9 degrees of freedom (11 results) the critical values of the correlation coefficient R at 5% and 1% significance are 0.602 and 0.735 respectively (Caulcutt, 1995). Where R is equal to or exceeds the critical value, the correlation is deemed significant. In Table 3.15, correlations significant at the 1% level are shown in red and at the 5% level in blue. There were no significant correlations between friction and abrasion (indicated by delta E). Note the significant correlations between T2stat5, T2dyn0 and T2dyn5.

Subramaniam *et al.* (1991) observed that the dynamic modulus of cotton increased when cross-linked with dimethylol dihydroxy ethylene urea (DMDHEU). There was a strong negative correlation between the dynamic modulus and abrasion resistance, i.e. the cross linked fabrics were more easily damaged. There was only a weak negative correlation between friction and dynamic modulus, again suggesting that the link between friction and abrasion was not apparent.

Abrasion resistance and wet wrinkle recovery was improved on cotton with non-reactive modification using long chain fatty molecules (Benerito *et al.*, 1971). Chemical

grafting of fatty molecules via esterification of the cotton improved dry crease recovery but decreased abrasion resistance. This suggests that non-reactive treatments would are preferable to reduce abrasion damage. In contradiction, however, Burkinshaw and Gandhi (1997) proposed that lyocell dyed with cross-linking, multi-functional reactive dyes has better abrasion resistance than non-dyed lyocell.

In practice the gums (xanthan, welan, and gellan) and bacterial polysaccharide would not be of use as lubricants when dyeing cellulose fabrics, since they would compete for dye molecules and alter the final shade of the fabric. They may be of use in other wet processes where an easily damaged polymer product slides against a hard surface.

On the basis of these results, coating a metal surface with a low friction polymer would be expected to give the best damage reduction. The manufacturers of some modern jet dyeing machines already use this approach, by lining fabric/machine contact surfaces with PTFE. Where this is not possible, due to inaccessibility or cost, the inert wax dispersion or PEO/PPO as additives may provide improvements over the existing lubricants used commercially.

3.4 THE EFFECT OF LUBRICANTS ON WET FABRIC CREASE RECOVERY

3.4.1 Introduction

In the previous section it was shown that lubricants can reduce wet fabric/metal abrasion. Another mode of action investigated here was wet fabric crease recovery. Damage marks, produced in dyeing and finishing, occur where a fabric has folded or where a crease has set in. The raised surface at the apex of a crease or fold is a prime zone for damage to occur. This is because the apex of the crease is the most

exposed area and will be the zone of closest contact with the metal machine surfaces. Preventing creases from setting and allowing the fabric to re-orientate folds could reduce white line and crows-feet damage marks, by spreading contact load over a greater area of fabric surface and changing the damage zone.

3.4.2 Experimental

Wet crease recovery was tested in the lubricant solutions used in the previous sections. Two fabric types were used, (i) a prepared lyocell fabric, consisting of Courtaulds lyocell fibres (1.7 dtex) in a Santanderina Q7027, 2/1 twill construction and (ii) a prepared lyocell fabric using the same fibres as (i) but in a UCO, plain weave construction (165 gm^{-2}). The angle of recovery was determined after a fabric was folded and creased under a static load.

For each lubricant applied to the twill fabric, 12 rectangular specimens each 50mm x 25mm were cut. Half had the 50mm dimension in the warp direction and the other half had the 50mm dimension in the weft. When testing each lubricant in a particular direction, three folds were made with the fabric face to face and the remaining three were made with the fabric back to back.

For each lubricant applied to the plain fabric, ten specimens were cut, five with the 50mm dimension in the warp direction and the other five with the 50mm dimension in the weft. Samples were tested face to face only, although this was less important than with a twill since the plain weave did not have a discernible face or back.

Fabrics specimens were soaked in the liquids for at least 24 hours before testing. Before each test, specimens were sandwiched between blotting paper and pressed lightly to remove excess liquid. A crease recovery angle tester and loading device

manufactured by James H. Heal and Co. Ltd. was used in all experiments. A 2kg load was applied for 60 seconds then removed and the specimen was transferred to the angle tester. A further 60 seconds was allowed before measuring the recovery angle.

3.4.3 Results and Discussion

Results from the tests are summarised in Tables 3.16 to 3.19.

Table 3.16 Warp Crease Recovery Angles (degrees) for Twill Fabric Soaked in Various Liquids

Liquid	Face #1	face #2	face #3	back #1	back #2	back #3
Water	35	37	26	103	98	82
Perilan	26	30	26	84	108	105
Cibafluid	33	29	24	72	85	112
Sandoperm MEJ	35	29	29	125	132	135
PEO/PPO	42	46	41	101	106	93
Wax/leomin	53	32	30	110	107	104
Bacterial PS	33	37	34	101	91	110
Xanthan	30	38	30	85	87	89
Welan	36	31	30	82	96	104
Gellan	43	42	47	106	110	112

Table 3.17 Weft Crease Recovery Angles (degrees) for Twill Fabric Soaked in Various Liquids

Liquid	Face #1	face #2	face #3	back #1	back #2	back #3
Water	90	77	95	93	88	91
Perilan	110	96	75	70	99	112
Cibafluid	88	109	90	73	97	96
Sandoperm MEJ	120	105	136	110	85	87
PEO/PPO	91	95	102	66	109	103
Wax/leomin	68	81	64	84	62	76
Bacterial PS	101	99	114	105	83	110
Xanthan	96	114	99	95	61	91
Welan	108	104	91	81	85	78
Gellan	86	95	81	91	100	83

Table 3.18 Warp Crease Recovery Angles (degrees) for Plain Weave Fabric Soaked in Various Liquids

Liquid	result #1	result #2	result #3	result #4	result #5
Water	50	50	52	47	52
Perilan	39	50	49	64	70
Cibafluid	68	69	79	62	71
Sandoperm MEJ	75	48	70	49	48
PEO/PPO	41	50	44	50	54
Wax/leomin	40	70	51	46	72
Bacterial PS	73	49	45	91	46
Xanthan	77	55	52	84	51
Welan	56	62	79	65	77
Gellan	53	42	50	46	39

Table 3.19 Weft Crease Recovery Angles (degrees) for Plain Weave Fabric Soaked in Various Liquids

Liquid	result #1	result #2	result #3	result #4	result #5
Water	79	87	81	76	82
Perilan	70	81	59	79	93
Cibafluid	81	73	65	80	80
Sandoperm MEJ	80	87	100	86	77
PEO/PPO	70	92	71	64	71
Wax/leomin	62	76	69	86	76
Bacterial PS	78	83	60	71	101
Xanthan	70	71	90	92	73
Welan	94	67	80	86	72
Gellan	71	80	82	70	86

The data contained in Tables 3.16 to 3.19 were subjected to analysis of variance (ANOVA) tests. Using the output of the ANOVA tests, Duncan's new multiple range test (Statistics for Industry, 1996) was employed to group similar lubricants, in terms of their crease recovery angles. The test also shows which lubricants give differences at the 5% significance level. The bands in Tables 3.20 to 3.25 indicate which results overlap and are not significantly different. The numbers shown in the tables are average crease recovery (CR) angles in degrees.

Table 3.20 Grouping of Crease Recovery Results for Twill Fabric, Warp Direction

Face to Face

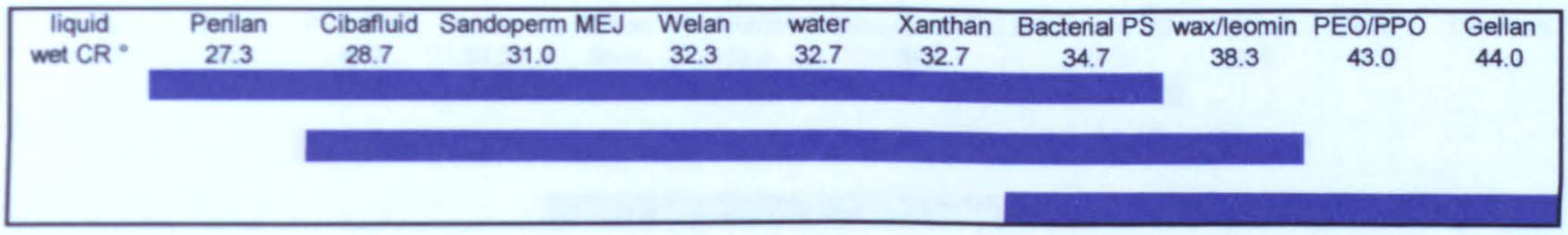


Table 3.21 Grouping of Crease Recovery Results for Twill Fabric, Warp Direction

Back to Back

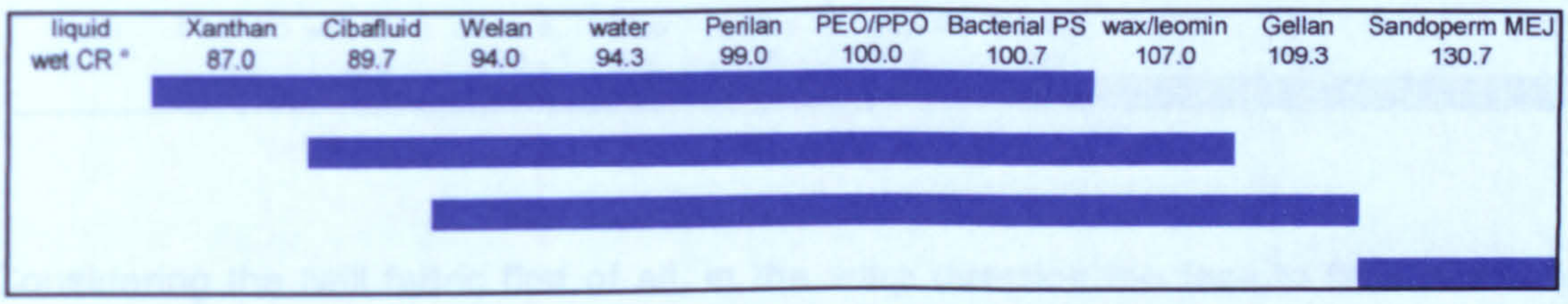


Table 3.22 Grouping of Crease Recovery Results for Twill Fabric, Weft Direction

Face to Face

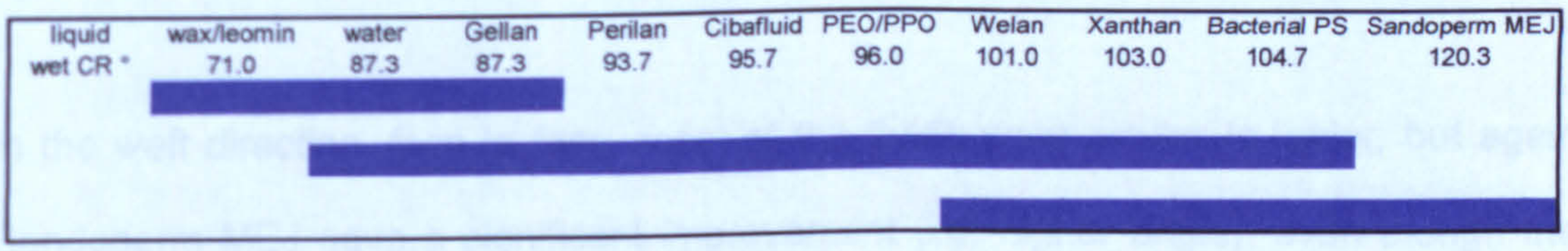


Table 3.23 Grouping of Crease Recovery Results for Twill Fabric, Weft Direction

Back to Back

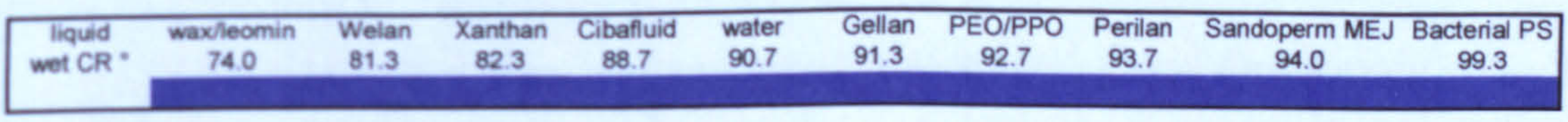


Table 3.24 Grouping of Crease Recovery Results for Plain Weave Fabric, Warp Direction

liquid	Gellan	PEO/PPO	water	Perilan	wax/leomin	Sandoperm MEJ	Bacterial PS	Xanthan	Welan	Cibafluid
wet CR °	46.0	47.8	50.2	54.4	55.8	58.0	60.8	63.8	67.8	69.8

Table 3.25 Grouping of Crease Recovery Results for Plain Weave Fabric, Weft Direction

liquid	PEO/PPO	wax/leomin	Cibafluid	Perilan	Gellan	Bacterial PS	Xanthan	Welan	water	Sandoperm MEJ
wet CR °	73.6	73.8	75.8	76.4	77.8	78.6	79.2	79.8	81.0	86.0

Considering the twill fabric first of all, in the warp direction the face to face recovery angles were low (27° to 44°). Only the wax dispersion, PEO/PPO and gellan solutions gave any significant increase in recovery compared to water. Back to back angles were higher (87° to 131°). Here most liquids tested were similar to water and only Sandoperm MEJ increased the recovery angle significantly.

In the weft direction, face to face, most of the fluids were similar to water, but again Sandoperm MEJ gave a significant improvement (*i.e.* higher angle), even though the performance overlapped with some of the other lubricants (welan, xanthan and bacterial polysaccharide). Recovery angles were in the range 71° to 120°. Back to back angles were in the range 74° to 99° with no significant differences between any of the liquids.

With the plain weave in the warp direction, most liquids had similar recovery angles to water but welan and Cibafluid gave significant increases. The warp recovery range was

46° to 70°. There were no significant differences in the weft direction (range of 74° to 86°).

For both fabrics, twill and plain weave, weft crease recovery angles were similar (71° to 120° overall), however the recovery angle of the twill fabric in the warp direction depends on whether the fold is face to face or back to back. Face to face recovery angles (27° to 44°) were lower than back to back (87° to 131°). The plain weave warp recovery angles (46° to 70°) were in between the two sets of warp results from the twill. The recovery angles are lower than the 155° wet recovery of cotton print cloth reported by Benerito *et al.* (1971).

Overall the largest increases in wet crease recovery angle were obtained Sandoperm MEJ, but only in specific fold directions. No lubricant gave increases in all directions, so a universal improvement in wet crease recovery is deemed not attainable with these lubricants compared to water.

The use of cross-linking resins to improve crease recovery has been known for some time (Marsh, 1962). Crease recovery has been modelled in terms of spring and dash pot elements. These represent friction and bending, flow and yield properties leading to permanent fibre deformation (Lindberg, 1961, Hilyard *et al.*, 1972). Cross-linking mainly affects the yield mechanisms, which are time dependent. The speed and duration of loading affect the fabric response. Chapman (1975) suggested that a fabric would recover completely from wrinkling if friction were not present. However, residual deformation can build up over a number of wrinkle cycles, and time dependent relaxation can occur, which is independent of friction.

Skelton (1968) proposed that crease recovery is a function of the elastic properties of fibres, the geometry and construction of the fibres, yarns and fabrics, fibre/fibre and

yarn/yarn friction and finish treatment. Dry crease recovery angles for plain weave cotton and viscose fabrics were given as 73°-103° and 80°-129° respectively.

Hjalmarsson and Åsnes (1972) showed wet crease recovery angles for woven cotton fabric in the range 50°-100°. The measured angles were shown to be dependent on recovery time. The length of time over which the crease was formed was not so important. Creases which formed during swelling recovered less than those which formed after swelling was complete. The creasing behaviour of fabrics which contained polyester was shown to be temperature dependent, but cotton fabrics were not temperature sensitive. Wilson and Hoffman (1959) also studied swelling and crease recovery. A resin treated, wet cotton fabric was shown to rapidly increase the recovery angle as drying commenced (after ~30 minutes). Initially, restraint was imposed on the fabric recovery due to swelling and friction. The effect was only observed with fabrics containing cellulosic fibres.

Nielson and Elder (1975) concluded that the formation of crease marks in cotton fabric was unrelated to the crease recovery angle and that creases can still form whether the recovery angle is large or small and irrespective of whether or not the fabric is finished. No great differences in wet crease recovery were found in the present work when various lubricants were employed. Even if significant differences in recovery angles had been seen, Nielson and Elder's work suggests that they may not be a true reflection of crease reduction in practice.

Reduction in fabric damage by using lubricants in wet processing is more likely to be achieved by reducing abrasion and protecting the fabric folds as they are dragged over metal machine surfaces, rather than attempting to improve wet crease recovery.

3.5 CONCLUSIONS

Solutions of a silicone softener (Sandoperm MEJ), a fabric conditioner (Comfort), a major component of fabric conditioners (DSDMAC), oleic diethanolamide surfactant, acrylamide/acrylic acid copolymer and a wax dispersion produced the lowest wet fabric/metal static friction forces, amongst the solutions tested. These lubricants all reduced static friction significantly compared to water. The lowest of all wet static friction was observed when the metal surface was covered with polyethylene film.

Dye liquor and the silicone softener (Sandoperm MEJ) produced the lowest wet fabric/metal dynamic friction forces, although some of the other solutions tested also reduced dynamic friction significantly in comparison to water. The reactive dye (Procion H-ER 150) and glaubers salt were the components of dye liquor which were responsible for the reduction in friction. Gum solutions and a bacterial polysaccharide in water generally exhibited higher dynamic friction forces as a consequence of their increased viscosity.

A Martindale test was not sensitive enough to reveal differences in the wet abrasion resistance of lyocell fabric against metal, when lubricated with various solutions. A crock test, together with colour measurements of damaged and undamaged regions of abraded fabric, was shown to be successful in distinguishing differences in the abrasion protection of various lubricants.

A bacterial polysaccharide, gum solutions (xanthan, welan and gellan), a wax dispersion, a PEO/PPO polymer solution and a commercial lubricant (Perilan VF) all reduced abrasion damage compared to water. The best protection was provided when the metal crocking pin was covered with poly(ethylene) film. The silicone softener (Sandoperm MEJ) solution produced the worst abrasion damage, probably because it's

good lubricating action allowed fibres to lift out of the fabric. The loose fibre ends could have become extreme contact points, subjected to severe abrasion.

In this work, there was no significant correlation between wet fabric/metal friction forces and the level of abrasion damage produced by the various lubricating systems.

None of the lubricants studied in the abrasion tests produced an overall increase in the wet crease recovery of woven lyocell fabrics, although the silicone softener (Sandoperm MEJ) produced some increases in recovery angle, but only in specific fold directions.

CHAPTER 4

SUMMARY AND FINAL CONCLUSIONS

Lubrication is an important consideration in many industrial processes. In textile production, control of friction via lubrication is essential if high quality consistent goods are to be produced. This present work was concerned with two particular aspects of textile lubrication:

(i) fibre finishing to modify friction in carding, drafting and spinning processes and

(ii) lubrication to reduce wet fabric damage during dyeing and finishing.

Although in practice many fibre types are processed into yarns and finished fabrics, in this work cellulosic fibres and fabrics were targeted for study.

4.1 SUMMARY OF THE WORK ON DRY LUBRICATION OF FIBRES

Fibre finishes are essential aids in converting staple fibres into yarns. Friction and static electricity generation must be controlled for successful processing. There are a variety of methods for applying finish, such as spraying, immersion in a bath or direct application by kiss roll or metered application.

There are several ways of analysing the deposited finish. Many rely on extraction of the finish from the fibres, whilst others analyse the treated fibres directly. Most of the analysis techniques have shortcomings. In the present study SIMS was shown to be a viable analysis tool to complement the other available techniques. Direct chemical information was provided from finished fibre surfaces without the need for finish extraction.

The lubrication of wet fabrics during dyeing and finishing is also an important issue. Some cellulosic fabrics are damaged in the wet state when they are dragged over metal machine surfaces. Polymeric lubricants are often used to reduce abrasion damage, but there is no evidence in the literature of a thorough understanding of the mechanisms by which these lubricants provide protection.

Many studies of the friction of fibres, yarns and fabrics conclude that in general, textiles do not follow the usual rules associated with the friction of metals. This is because there is some degree of elasticity present in polymers. Textile friction depends on a number of factors: load, speed, relative humidity and moisture content, physical form of the fibres (shape, polymer type, orientation, etc.), lubricant viscosity and so on. Several methods are reported in the literature as being suitable for the measurement of fibre friction. In this work, fibres were draped over a pin with a known load on one end and the force between the pin and fibres during sliding was measured. This was deemed the most appropriate method to compare the effects on static and dynamic friction of a variety of finish treatments on viscose fibres. The method was also used to measure friction between fabric and metal under wet conditions.

In a designed experiment, the effect of deposition conditions during finish application, on finish pick-up and finished fibre friction was investigated. A model finish containing lubricant and antistat components was applied from emulsion onto viscose fibres. The ratio of the two components, emulsion concentration, deposition bath temperature and dip time were varied. Using SIMS in conjunction with conventional finish extraction analysis, it was shown that there was no significant correlation between the finished fibre surface composition and the bath deposition conditions. This suggests that it is not feasible to

control the surface finish distribution by changing the finish bath parameters. However, the amount and composition of the finish extracted from the fibre bulk was affected by the application conditions. The amount of finish deposited increased with higher emulsion concentration. Also, more antistat relative to lubricant in the bath produced more antistat relative to lubricant deposited through the fibre bulk.

The emulsion concentration of the bath was the only variable which had a significant effect on fibre/metal friction of the bath finished viscose fibres. Increasing the bath concentration reduced fibre/metal friction (both static and dynamic). Unfinished fibres demonstrated the highest static and dynamic fibre/metal friction, and they also showed the largest stick-slip effect. Overall, bath finished viscose showed the lowest fabric/metal friction and the smallest stick-slip difference. The oversprayed viscose fibre metal friction parameters were intermediate between unfinished and bath finished fibres.

In contrast, fibre/fibre friction was not affected by any of the deposition variables, whichever method was used to apply the finish. Also, no significant differences were found between the fibre/fibre friction of unfinished and finished viscose.

When the two-component finish was spray-applied on viscose from both dilute and concentrated emulsions, SIMS spectra suggested that some fibre regions remained unfinished. The amounts of finish extracted from the sprayed, dried fibre specimens were less than the amounts deposited in the emulsions, suggesting some loss of finish during mangling and drying.

The dependence of fibre/metal friction on load was investigated. Finished viscose demonstrated behaviour similar to plastic materials (e.g. metals), suggesting that the usual friction rule for metals ($F=\mu R$, where F is the friction force, R is the normal load and μ is the friction coefficient) was close to being obeyed. This is in contrast to reports in the literature concerning fibre/fibre contacts, where there is a departure from ideal metallic behaviour due to elasticity.

Fibre/metal and fibre/fibre friction coefficients were calculated from the results of the present study. The coefficients were in general agreement with the range of literature values found for cellulose fibres, yarns and fabrics, however, the range of published values is large and the results depend on the conditions under which measurements were made.

It is important to control static charge accumulation during fibre processing. The electrical resistance of fibre bundles was used to indicate static dissipation performance. None of the bath finish deposition variables had a significant effect on the resistance of the finished viscose specimens. This implies that it is not possible to alter the electrical resistance, and hence static dissipation performance, by changing finish bath conditions. Unsurprisingly, unfinished fibres had a higher resistance than those which were bath finished. Oversprayed samples had resistance values similar to unfinished fibre. This could be because the applied finish does not form a continuous conductive film on oversprayed fibres.

The first part of this investigation suggests that bath deposition of finishes gives the best coverage of finish on fibre. An even deposit of finish is often given as a requirement for consistent fibre processing, hence, where possible bath application is preferable. Fibre/metal friction can be reduced by increasing the bath concentration. To optimise carding, this is a potential lever for improvement, since good carding is linked with low fibre/metal friction. Fibre/fibre friction was not altered by the finishes used in this study. Fibre cohesion and scroop, which are also deemed important to control for successful processing, would have to be altered by other factors such as fibre crimp. Finally, electrical resistance does not seem to be dependent upon finishing conditions or emulsion composition, as long as the finish is applied by immersion. This suggests that more of the cheaper lubricant components can be used in preference to more the expensive antistat, without compromising static dissipation performance.

4.2 SUMMARY OF THE WORK ON WET LUBRICATION OF FABRICS

From a range of surfactants, polymeric lubricants, softeners, commercial lubricants and bio-polymers, the best reductions in low speed (static), wet fabric/metal friction were obtained with a silicone softener, a wax dispersion, a diethanolamide surfactant, a poly(acrylamide co-acrylic acid) polymer, a fabric conditioner (comfort) and a main component of fabric conditioners (DSDMAC). The lowest wet fabric/metal static friction was achieved when the metal surface was covered with poly(ethylene) film, suggesting that coating a metal machine surfaces with a polymer might be a good way to reduce friction and hence abrasion damage to wet fabric.

Dye liquor and liquors containing some of the lubricants gave the lowest dynamic wet fabric/metal friction. The dye and glaubers salt were the liquor components responsible

for lowering dynamic friction. It is possible that these components increase the fabric stiffness and reduce the area of sliding contact, hence lowering friction. The bio-polymer and gums (xanthan, welan and gellan) tended to increase dynamic friction as a consequence of increasing the lubricant fluid viscosity.

With a knowledge of which lubricants gave the best reductions in friction, abrasion performance was assessed. Initial attempts using a Martindale method were unsuccessful, since the test was not sensitive enough to reveal differences between the lubricants. A modified crock test did however reveal differences between lubricants in wet fabric/metal abrasion damage. The level of damage was quantified by measuring colour differences between rubbed and undamaged regions of the fabric. The bacterial polysaccharide, the gums, the wax dispersion and the PEO/PPO block copolymer solution all reduced abrasion damage significantly, when compared to water. The best reduction in damage was achieved when the metal abrading pin was covered with poly(ethylene) film. As with the friction results, this suggests that the best protection of wet fabrics in dyeing and finishing machines might be obtained if the metal contact surfaces are coated with a suitable polymer.

Surprisingly, one of the lowest friction lubricants, a silicone softener, produced the worst abrasion damage. A plausible explanation is that the silicone is so good at lubricating, that it causes fibres to work loose from the yarns in the fabric. During abrasion these are uppermost on the fabric surface and are therefore most prone to damage.

No statistically significant correlation was found between the measured friction parameters and abrasion damage in these experiments, although poly(ethylene) film gave the lowest static wet friction and also the lowest level of abrasion damage.

The bacterial polysaccharide and the gums are not suitable as lubricants for the dyeing and finishing of cellulosic fabrics, since polysaccharides would show substantivity to dye molecules and interfere with the dye uptake of the fabric. Their uses in other applications should not be ruled out though, since they have clearly been demonstrated to have a protective effect.

The friction and abrasion reducing performance of commercial dyeing and finishing lubricants is, in general, not too dissimilar to that of water. Some of the novel lubricants in the present study gave greater friction reductions and better abrasion protection, so there seems to be scope for improvement of the commercial lubricants.

None of the lubricants studied gave an overall increase in wet fabric crease recovery angles. This observation suggests that a reduction in fabric damage during wet processing, is more likely to be achieved through protecting the fabric whilst it drags on machine surfaces, rather than relying on the lubricant to help to shed creases in the wet fabric.

4.3 OVERALL CONCLUSIONS

• With an appropriate calibration, SIMS is a viable tool for the direct analysis of the composition and distribution of finish on fibres.

• When finish is applied to viscose fibres from a bath, the surface composition of finished fibres does not necessarily reflect the bath composition. The dip time and temperature of the bath may not affect the composition of the deposited surface either.

• The total amount of finish extracted from the viscose fibres depends on the bath emulsion concentration. A higher concentration in the bath was found to produce more finish on fibre. More antistat in the bath resulted in more antistat being deposited through the fibre bulk.

• The emulsion concentration in the bath was the only factor found to affect static and dynamic fibre/metal friction. The higher the bath concentration, the lower the fibre/metal friction. The ratio of antistat to lubricant in the bath, the dip time and the bath temperature did not significantly affect fibre/metal friction.

• For fibre/fibre contacts (unlike fibre/metal contacts), none of the finish bath variables (emulsion concentration, ratio of antistat to lubricant in the bath, the dip time and the bath temperature) were found to affect static or dynamic friction.

• Spraying finish onto viscose fibres resulted in unfinished regions. The surface composition and total amount of finish deposited did not reflect the quantity of finish applied in the sprayed emulsion.

• Bath application produced lower static and dynamic, fibre/metal friction than overspraying. Unfinished viscose fibres produced the highest friction forces and the

largest stick-slip difference at low speed. The application of finish and the method of deposition made little difference to fibre/fibre friction.

• On average, static fibre/fibre friction forces were greater than static fibre/metal friction forces, although there is little difference between the fibre/metal and fibre/fibre dynamic friction forces.

• The friction coefficients measured in this work are in general agreement with the range of values reported in the literature. Friction coefficient values do, however, depend on the method of measurement.

• Bath conditions (emulsion concentration, ratio of antistat to lubricant in the bath, the dip time and the bath temperature) did not significantly affect the electrical resistance of finished viscose fibres. Oversprayed fibres had higher resistance than bath-finished fibres (similar in magnitude to unfinished fibre). The high resistance of oversprayed fibres is perhaps due to the discontinuous coverage by lubricant and antistat.

• Solutions of a silicone softener (Sandoperm MEJ), a fabric conditioner (Comfort), a major component of fabric conditioners (DSDMAC), oleic diethanolamide surfactant, acrylamide/acrylic acid copolymer and a wax dispersion gave low wet fabric/metal static friction forces compared to water. The lowest wet static friction was observed when the metal surface was covered with poly(ethylene) film.

• Dye liquor and Sandoperm MEJ gave the lowest wet fabric/metal dynamic friction forces, although some of the other solutions tested also reduced dynamic friction in comparison to

water. Procion H-ER 150 (dye) and glaubers salt were the components of dye liquor responsible for the reduction in friction. Solutions of xanthan, welan and gellan gums and a bacterial polysaccharide in water produced higher dynamic friction forces as a consequence of their increased viscosity.

• The Martindale test is not sensitive enough to reveal differences in the wet abrasion resistance of lyocell fabric against metal, when lubricated with various solutions. A crock test, together with colour measurements of damaged and undamaged regions of abraded fabric, works well in assessing abrasion protection.

• Bacterial polysaccharide and xanthan, welan and gellan gum solutions, a wax dispersion, a PEO/PPO polymer solution and a commercial lubricant (Perilan VF) all reduced abrasion damage compared to water. The best protection was provided when the metal abrading surface is covered by poly(ethylene) film. Sandoperm MEJ produced excessive abrasion damage.

• No significant correlation was seen between wet fabric/metal friction forces and the level of abrasion damage produced by the various lubricating systems.

• None of the lubricants studied in the abrasion tests gave an overall increase in the wet crease recovery of woven lyocell fabrics, although the silicone softener (Sandoperm MEJ) did produce increased recovery angles in specific fold directions.

4.4 SUGGESTIONS FOR FURTHER WORK

(i) The application of SIMS should be extended to the analysis of finish systems with more than two components.

(ii) The determination of finish distribution could be refined by using SIMS imaging of fibres both longitudinally and in cross section (to check for diffusion of components into the fibres). This might help to explain the differences between surface and bulk finish composition on fibres.

(iii) The present study could be extended to determine how finish deposition conditions, the resulting finish composition and distribution, and the resultant friction behaviour affect the quality of processing from fibres to yarns.

(iv) An investigation into how the wet tensile, compression and shear properties of cellulose fibres are affected by dye liquor and its components would be of interest in relation to friction and abrasion properties. Such a study should take account of the relevant range of temperatures in wet processing.

(v) Further fundamental study of the action of low concentration polymeric lubricants in friction and abrasion reduction is required if useful improvements to marketed products are to be made.

(vi) The application of durable polymeric coatings on metal machine surfaces, which cause abrasion damage to wet fabrics, should be investigated.

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